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Reports
Bevins,
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Fire Simulation Modeling

FINAL REPORT FOR RESEARCH JOINT VENTURE AGMT
#INT-90482-RJVA with
SYSTEMS FOR ENVIRONMENTAL MANAGEMENT
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INT-90482-RJVA

Fire Simulation Modeling

Final Report

November 1993

Collin D. Bevins
Systems for Environmental Management
Missoula, MT

This is the final report for Research Joint Venture Agreement INT-90482-RJVA between the Intermountain Station and Systems for Environmental Management.

The objectives of the agreement as specified in the *Work Plan* are:

- To investigate available computer technologies to support the development of a cooperative ecological simulation architecture.

- To select an appropriate set of technologies and implement them in a "proof of concept" demonstrating the viability of the cooperative ecological simulation architecture.

The following products have been produced by this study:

- Bevins, C.D., Andrews, P.L. 1993. The Loki Software Architecture for Fire and Ecological Modeling: A Tinker Toy Approach. A paper presented at the twelfth Conference on Fire and Forest Meteorology, October 26-28, 1993, Jekyll Island, GA.

- Andrews, P.L., Bevins, C.D. 1993. Fire Growth Simulation for Prescribed Natural Fire. Paper presented at the Symposium on Fire in Wilderness and Park management: Past Lessons and Future Opportunities, March 30 - April 1, 1993, Missoula, MT.

- Andrews, P.L., Bevins, C.D. 1992. Fire Growth Simulation Model- An Element in the Integrated Fire Management System. Report presented at Fire and Meteorology Resource Spatial Analysis workshop, Feb 26-28, 1992, Tucson, AZ.

- Bevins, C.D. 1992. Fire Simulation Modeling Work Plan.

- Bevins, C.D. 1993. Fire Simulation Modeling Progress Report.

- Bevins, C.D. 1993. Loki: Proof of Concept.

- All source code for the Loki Session Manager and client programs constituting the proof of concept are available in printed and electronic form at the Intermountain Fire Sciences Lab, Missoula, MT.

- A color slide presentation and script describing the Loki evolution, components, and benefits is on file at the Intermountain Fire sciences Lab, Missoula, MT.

THE LOKI SOFTWARE ARCHITECTURE FOR FIRE & ECOSYSTEM MODELING: A TINKER TOY APPROACH[1]

C. D. Bevins and P. L. Andrews[2]

ABSTRACT: Loki is a software architecture that enables any number of concise, domain-specific simulation models (clients) to operate and communicate concurrently as an integrated, holistic ecosystem simulation. Each client runs as a separate process on a UNIX workstation network running X Windows. The Loki session manager synchronizes the event-driven simulation, enables communication between its simulation clients, and provides access to shared spatial data. The Loki Application Programmers' Interface allows clients to communicate with the session manager, receive and schedule events, and access and update map data. Client types include simulation models, 2- and 3-dimensional visualizations, interfaces to geographic information systems and statistical packages, screen and data capture utilities, and user interaction. Loki offers (1) ease of constructing holistic simulations from a tool box of client models for a variety of applications (e.g., research, management, training, decision support, policy making, and public information), (2) improved integration of simulations from a broad range of scientific disciplines, and (3) simplified coding of clients through the API, which offers independence from map location, format, extent, resolution, registration, input/output, units, and datum type.
KEYWORDS: ecosystem modeling; fire modeling; system integration

INTRODUCTION

Renewed emphasis on ecosystem management and global climate change, combined with ever more powerful and affordable computer hardware, is inevitably attracting more scientists into the realm of holistic, large scale ecosystem modeling. The arena of fire behavior and effects simulation alone encompasses a broad spectrum of spatially and temporally variable ecosystem processes spanning climate, weather, moisture, topography, soils, fuels, fire ignition, fire spread, fuel consumption, smoke production, vegetation mortality, and succession. Research into these processes is underway at laboratories and universities around the world. Once developed, there are many potential applications for such simulations: research, planning, decision support, training, and public information. Andrews (1989) discusses several applications for fire growth models alone.

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[1]A paper presented at the 12th Conference on Fire and Forest Meteorology, October 26-28, 1993, Jekyll Island, Georgia.

[2]Collin D. Bevins is Director, Systems for Environmental Management, P.O. Box 8868, Missoula, MT 59807. Patricia L. Andrews is Project Leader, USDA Forest Service, Intermountain Research Station, P.O. Box 8089, Missoula, MT 59807.

A major challenge is how best to draw together the simulation efforts of experts in diverse disciplines and locations and implement them on increasingly capable hardware systems to meet the requirements of disparate user groups. We face this challenge even on a local scale; how do the scientists within our laboratory design, develop, test, and share their models to meet the varied needs of fire researchers, planners, trainers, managers, dispatchers, policy makers, and homeowners? This challenge led to the design and development of the Loki software architecture for cooperative ecosystem simulation.

LOKI DESIGN FEATURES

Loki's overall design objective is to make the development and implementation of large simulation applications as simple as possible at two distinct levels: application design and the client programming. The *application designer* works at a very high level, assembling an appropriate set of client programs into a simulation for a specific application and user group. The *client programmer* works on the coding of concise, encapsulated client programs for use by application designers. While one person may be both an application designer and a client programmer, the tasks performed in each role remain distinct.

Loki is an open, extensible architecture employing established hardware and software standards. It operates on UNIX workstation networks running the X Windows Systems and the Network File System (NFS).

Loki Design Features for Application Designers

Within the Loki framework, application designers work at the highest level of abstraction, freed from any programming tasks. The designer views an application as an arrangement of tinker toys or objects, and is concerned only with which objects to use and not how they operate or interact. Loki provides the following benefits to the application designer.

- Applications are designed simply by specifying a list of client programs, a list of map sources, a geographic extent, and a time span for the simulation.

- Application functionality and complexity is easily modified by swapping client programs in and out of the client list. The geographic location of a simulation is easily changed by modifying the geographic extent and map file list.

- Designers extend the functionality of their applications by incorporating clients developed by other context experts and contributed to the Loki tool chest.

- Applications are easily modified to test alternative clients, evaluate alternative configurations, and meet the requirements of various end users.

- Application designers can choose from a wide variety of client types as they become available. Client programs may be developed to:

  -- simulate chemical, physical, biological, climate, weather, production, succession, dispersion, migration, population, and other ecosystem processes,

  -- simulate human activity,

-- dynamically display and update 2- and 3-dimensional maps, graphs, sliders, gauges, and alarms during the simulation,

-- capture map data, summary statistics, and visual displays at selected times for later analysis or playback,

-- interact with the user on an ad hoc basis during the simulation to edit input data (e.g., weather streams), modify maps (e.g., change fuel types) start new clients (e.g., start a bulldozer), and schedule events (e.g., a lightning strike),

-- interpolate lattice, cell, or sample point data into continuous field variables using kriging, splining, or other techniques,

-- perform neighborhood, proximity, focal, or other spatial analysis functions,

-- pipe simulation data directly into concurrently running data base, GIS, or statistical analysis programs, and

-- accumulate map data within nested cell structures or between hierarchical modeling levels (e.g., summarizing organismic field variables to the stand, patch, or landscape levels).

- Applications can run multiple copies of the same client (e.g., several bulldozers can work separate segments of a fire containment line).

- Applications are event-driven rather than using a fixed time step. This allows each client to determine its own appropriate time scale, and enables real time ad hoc user interaction.

- Applications can run their clients across heterogenous networks supporting the X Windows and Network File System, making optimum use of computing resources.

Loki Design Features for Client Programmers

Loki treats each client program as separate, encapsulated process. Many of the tasks normally associated with large simulations, such as map input, output, and conversion, function synchronization, and resolving map-function interdependencies, are managed by the Loki session manager and the application programmers' interface (API). Loki provides the following benefits to client programmers.

- Clients programs are concise, encapsulated objects. They respond to session manager requests to (1) initialize themselves, (2) update their outputs, or (3) terminate themselves.

- The Loki session manager, and not client programs, handles all simulation synchronization, resolves all client-map dependencies, and determines when one client's output has modified another client's input.

- The API handles all map access and updating details; the programmer merely specifies the generic type of each map used by the client (e.g., "elevation"), its access mode (read, write, or update), the preferred units of measure for map dimensions and values, and the preferred datum type (e.g., integer, floating point). The programmer is freed from the details of map file names, location, format, extent, resolution, units of measure, and datum type conventions.

- The programmer is freed from writing any map input/output code. The API

allows the programmer to get and set map values at any cell or point, and automatically resamples the map with full missing value replacement. Multiple inputs maps may be referenced without regard to their native resolution or extent.

- The API provides client access, as needed, to any map parameters including native format, extent, resolution, units of measure, number of updates, and simulation time of last update.

- The API provides client access to the current simulation time, to the simulation's geographic extent, and to functions for date and time arithmetic and units conversion.

- The API allows a client to schedule callbacks to itself at any future time. A fire spread model, for example, asks the session manager to call it back when its next cell is scheduled to ignite. Similarly, a stand succession client may schedule a callback every 10 years to update its stand composition.

- The API provides a standard graphical user interface to each client, freeing the programmer from having to write user input/output code. If the client requires a custom graphical user interface, Loki is fully compliant with the X Windows System including the X protocols, Xlib, Xt widgets, and OSF Motif.

THE LOKI ARCHITECTURE

The Loki software architecture consists of four components (figure 1); the session manager, the API, shared maps, and client programs.

Loki Session Manager

The Loki session manager is a separate program responsible for coordinating the holistic simulation. It is an X Windows based program with a graphical user interface. The session manager maintains:

- the simulation's geographic extent,

- the client list,

- the shared map list,

- the client-map dependency table, and

- the simulation clock, event queue, and status.

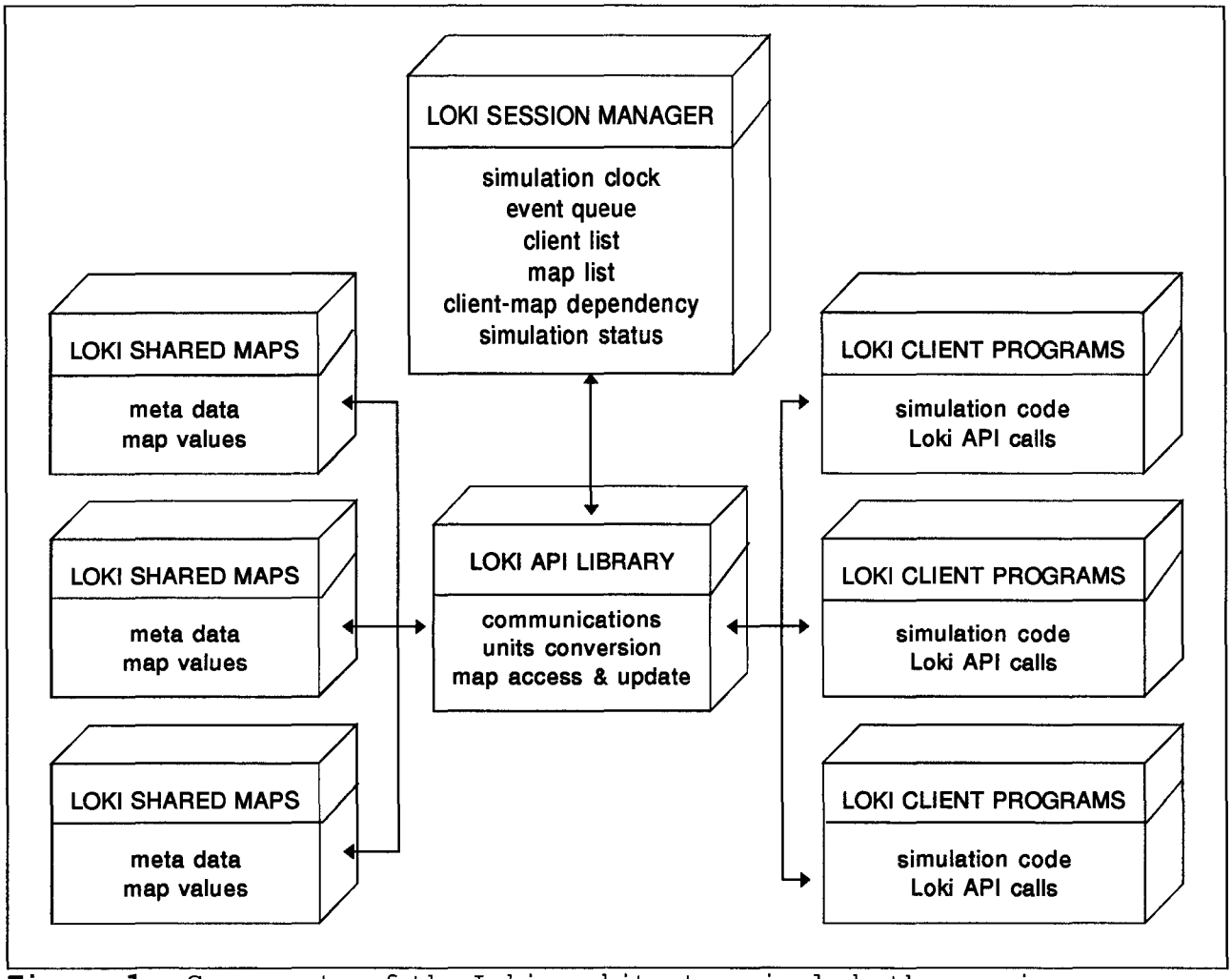

Figure 1 - Components of the Loki architecture include the session manager, API library, shared maps, and client programs.

The Application Programmers' Interface

The Loki API simplifies the design and coding of Loki client programs. It is an open library of documented POSIX and ANSI C function calls used by client programs to:

- register the client's generic input and output map types, map access, preferred dimensional and value units, and datum types with the Loki session manager,
- request the geographic extent, current simulation time, or map native resolution, extent, units, datum type, default and missing values, number and time of last update, or other map meta data,
- read or set the value for any map at any cell or point,
- schedule client callbacks at some future simulation date and time, and
- perform units conversions and date-time arithmetic.

Client Programs

Client programs are written using the API. Each client focuses on a single simulation, display, input/output, or analysis task. We hope developers will contribute their client programs to the Loki tinker toy chest to share among interested parties.

Loki clients are stand alone programs running as separate processes on a UNIX network. They communicate with the session manager and have access to shared maps via API function calls. Like the session manager, they are X Windows based programs and may have a graphical user interface (figure 2).

Client programs are invoked by the session manager, receiving command line arguments at run time just like any other program. The client contains functions that are called when the session manager requests it to (1) initialize itself (e.g., open support files, access data bases, allocate memory, process command line arguments), (2) perform a single simulation iteration, (3) stop or abort (e.g., free memory and close support files), and (4) terminate.

Shared Maps

Loki shared maps are dynamic file structures simultaneously accessible to all Loki clients via the API. The maps are standard NFS files whose access by clients is synchronized by the session manager. As NFS files, the maps may reside anywhere on the computer network.

Standards

UNIX, X Windows and NFS are important cornerstones of the Loki architecture. UNIX is the most widely used, open, multi-user, multi-tasking operating system in the world. It has extensive networking, virtual memory, and file sharing capabilities. The X Windows System provides communication and graphical display capabilities across heterogenous networks. Finally, NFS provides file access across the network.

STATUS

After a year of evaluating various technologies and developing initial designs, Loki has reached the proof of concept point. The session manager, API, shared maps, and an initial set of simulation and display clients have been successfully tested and demonstrated. The next step is to migrate the session manager and API to alpha test status with accompanying documentation. During this time we also hope to complete some 2- and 3-dimensional visualization clients and begin development of a family of fire behavior clients including:

- fuel array inference from stand maps and tables,
- newly developed litter and particle fuel moisture models,
- cell based fire spread algorithm with grid geometry bias removed (French 1992),
- non-cell based fire growth using Huygen's principle (Finney 1993), and
- newly developed crown fire spread models (Rothermel 1991).

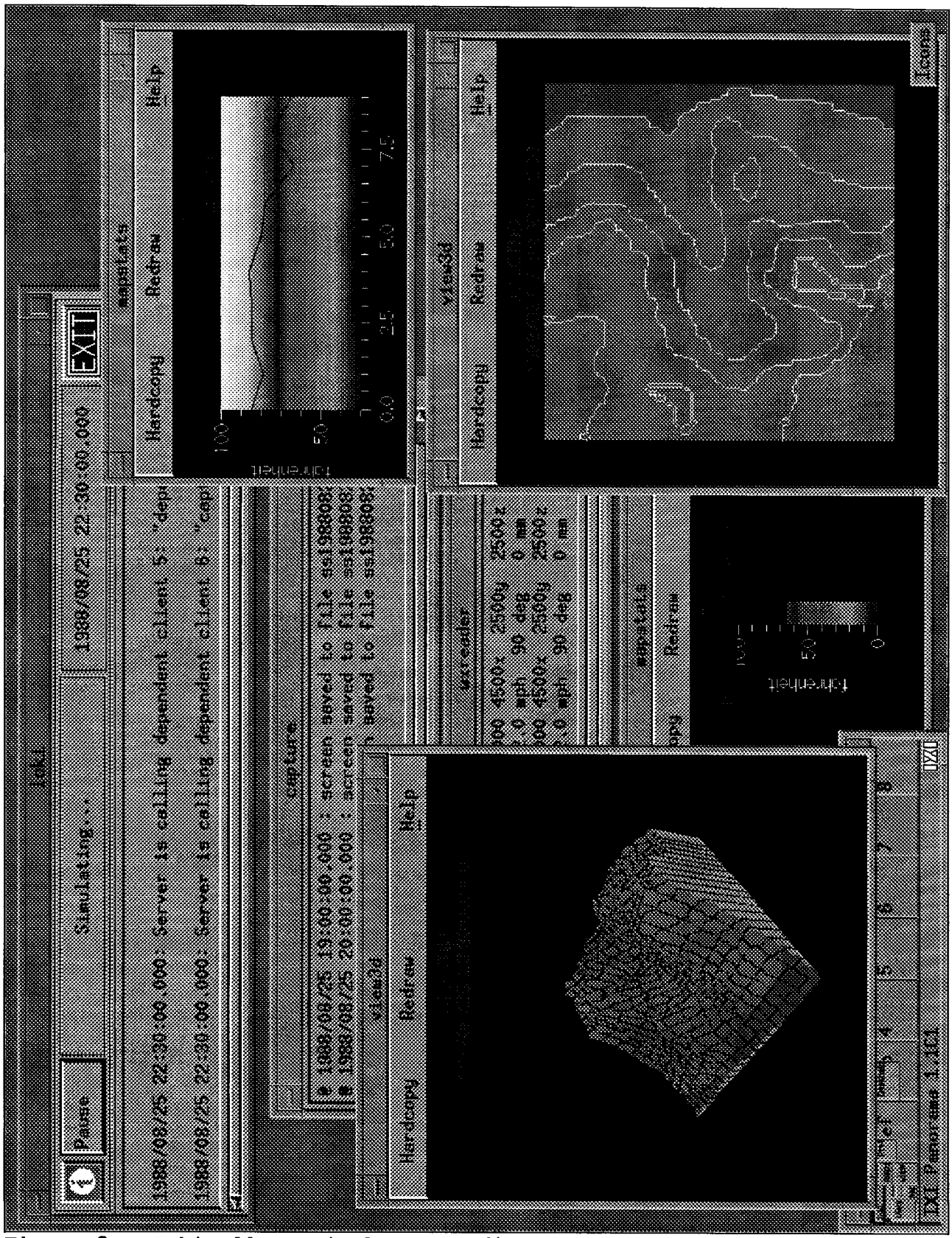

Figure 2 - Loki allows simultaneous display of multiple "live" maps and graphs during a simulation.

ACKNOWLEDGEMENTS

Funding and logistical support for the gestation of Loki has been provided by the US Department of the Interior, by the USDA Intermountain Research Station, and by Systems for Environmental Management.

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Editorial Draft 1

FIRE GROWTH SIMULATION FOR PRESCRIBED NATURAL FIRE[1]

Patricia L. Andrews Collin D. Bevins[2]

INTRODUCTION

Prescribed Natural Fire presents fire behavior prediction questions that go beyond those that have traditionally been asked about wildfire and management ignited prescribed fire. Time and location of ignition are not a choice as they are with management-ignited prescribed fire. And fire growth projections must go well beyond the next shift as is usually done for wildfire. In addition, ecosystem management questions are being asked about the role of fire in general, and prescribed natural fire in particular.

A fire growth simulation model under development by the Fire Behavior Research Work Unit and Systems for Environmental Management will help Prescribed Natural Fire (PNF) decisionmaking at several levels:

- -- Examination of fire policy with respect to ecosystem management considerations and wilderness management objectives,
- -- Development of fire management plans and prescriptions for prescribed natural fire,
- -- Designation of an ignition as a wildfire or a prescribed natural fire (the go/no-go decision), and
- -- Revalidation of the fire as a PNF throughout its lifetime.

We describe here features of the simulation and specifics of how we envision it being used for PNF in each of the four levels listed above.

APPROACH TO THE SIMULATION

The authors developed a GIS-based fire growth simulation to the point where the potential was evident. But rather than continue on the path toward the short term payoff of a demonstration product, we chose a more difficult path with a greater long-term payoff. The effort has been put into development of a software framework for fire and ecosystem modeling--designated "Loki" (Bevins and Andrews, in preparation).

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[1] Paper presented at the Symposium on Fire in Wilderness and Park Management: Past Lessons and Future Opportunities, Missoula, MT, March 30-April 1, 1993.

[2] Patricia L. Andrews is Project Leader, USDA Forest Service, Intermountain Research Station, P.O. Box 8089, Missoula, MT 59807. Collin Bevins is President, Systems for Environmental Management, P.O. Box 8868, Missoula, MT 59807.

In addition to PNF applications, the simulation will be used in other aspects of wildland fire management including training, determining wildfire suppression tactics, and economic analysis of fuel treatment options (Andrews 1989). For a simulation to be applied to the range of needs, it must be flexible. The Loki framework provides this flexibility.

Loki is based on the concept that system developers should be able to select models from a "tool box" and use them to build a system for a specific application. Models in that tool box can be independent entities developed by people in their own expertise domain. Models for fire spread, smoke production, tree mortality, and stand succession, for instance, can be developed independently and then incorporated into a single simulation system.

Loki will make it possible to select and package appropriate models for a specific application. For example, a current vegetation or fuel map and observed and forecasted weather would be used to simulate next day's growth of an ongoing fire. In the planning stages, however, a vegetation succession model, fuel accumulation and decay models, and climatology would be part of the simulation.

ECOSYSTEM MANAGEMENT AND FIRE POLICY

Wildland fire is an important factor in ecosystem dynamics (Williams and Rothermel 1992). The simulation can be used to examine the role of fire over hundreds of years by examining ecosystem and landscape change under various scenarios ranging from fire exclusion to allowing all fires to burn to the use of prescribed fire in selected locations; results can be compared to desired future conditions. In addition, design of the simulation will allow inclusion of other disturbances such as insect and disease or logging. Visual display of results can illustrate risks and ecological tradeoffs to policy makers and to the public.

FIRE MANAGEMENT PLANS AND PNF PRESCRIPTIONS

Once it is determined that there is a role for prescribed natural fire, fire management plans and prescriptions are written. The simulation is one of the tools that can be used in the process. It can be used to examine various "what-if" scenarios for fire location, time of year, fuel condition, and weather. A determination can be made of location and conditions under which PNF is an acceptable option. The simulation may also be used to examine the effectiveness of fuel treatment by management ignited prescribed fire or other methods for protecting structures, boundaries, or inholdings.

Weather conditions can be based to some extent on climatology, certainly for "most probable" scenarios. But one of the lessons of '88 was that "worst case" may not be in the weather records (Rothermel 1991). This is the time to define most probable and severe weather, not during the time crunch of a go/no-go decision.

THE GO/NO-GO DECISION

Many factors must be considered in making the decision to declare a new ignition a wildfire or a prescribed natural fire; potential fire growth is one of them. Day to day growth is not as important as final perimeter location with respect to the maximum allowable perimeter established for the fire. The question is whether the fire will cross a given line before it goes out.

The short-term forecast done by a Fire Behavior Analyst for the next shift on a wildfire (Rothermel 1983) is not sufficient nor appropriate for PNF. For PNF it is necessary to go well beyond the point where reliable weather forecasts are available. The simulation will aid thinking in terms of probability and risk. It is not possible to predict exactly what the fire will do, but the simulation will permit "gaming" of possible outcomes.

The obvious difference between using the simulation for developing a prescription and for examining possible fire behavior after the ignition has occurred is that we now know the location, time of year, state of fuels, and the weather to date. The simulation can incorporate current conditions and most probable and severe weather scenarios that were defined earlier, as well as long-term trend forecasts (McCutchen and others 1991).

Risks associated with various scenarios can be displayed to decisionmakers. And once a PNF decision has been made, display of simulation results can be used to explain decision process and fire potential to the public.

REVALIDATION AS PNF

As the fire progresses, more information becomes available, including observations of actual fire behavior. The simulation must be able to use information from the fire itself, in addition to mathematical fire spread models. In addition to gaming long-term behavior, daily projections based on weather forecasts can be made, like those done by an FBA on a wildfire.

FEATURES OF THE SIMULATION

In keeping with the decision to go with the long-term payoff, we are designing the simulation for "fast" Unix-based workstations with "lots" of memory and storage. Computer technology is advancing so rapidly that we feel that this is the proper approach.

We recognize that there will not be an accepted computer hardware and software standard among land management agencies for some time, if ever. Therefore, coding of the Loki software framework is being done in the C programming language and does not require a specific brand of GIS software. Conversion routines can be developed for various file structures.

The simulation will have a sound, well-documented scientific base. Visually appealing products make it easy to overlook the internal workings (guts) of a system. We are concentrating on both: the all-important visualization and improved models for fire behavior and growth. Loki will be a research tool in that mathematical models under development can be easily tested and compared.

We foresee that the fire growth simulation under development will be used for many fire management activities, including various levels of prescribed natural fire decisionmaking. The Loki software framework for fire and ecosystem simulation will provide the needed flexibility.

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INT-90482-RJVA

Fire Simulation Modeling

Progress Report

August 1993

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Introduction

This paper reports the progress achieved on research joint venture agreement INT-90482-RJVA between the Intermountain Station and Systems for Environmental Management.

The objectives of the agreement as specified in the *Work Plan* are:

- To investigate available computer technologies to support the development of a cooperative ecological simulation architecture.
- To select an appropriate set of technologies and implement them in a "proof of concept" demonstrating the viability of the cooperative ecological simulation architecture.

The work accomplished to date is summarized under the following headings:

- UNIX workstation and software setup and installation,
- review of technologies,
- development of code libraries,
- development of the prototype Loki system,
- collaboration with colleagues, and
- paper presentations and conference attendance.

Workstation Setup & Software Installation

The installation of UNIX workstation hardware and software usually required the detailed reading of installation manuals and a working knowledge of the software package acquired by reading manuals and using the product.

Hardware Installation

- Assist installation of Tektronix Phaser II printer and software.
- Assist installation of SPARCprinter printer and software.
- Install color page scanner hardware and software

System Software Installation

- Install NEWSprint 1.0. network printing software
- Install NEWSprint 2.0 network printing software
- Install OSF/Motif V1.1.3 windowing system
- Install OSF/Motif V 1.1.4 windowing system
- Install OSF/Motif V 2.0 windowing system
- Install SUN AnswerBook software and quarterly updates
- Install SUNSolve software and quarterly updates
- Install SoftPC PC emulation software

C Development Installation

- Install EDIX text editor
- Install Speed Edit text editor
- Install Slick Edit text editor
- Install SUN ANSI C compiler
- Install Lucid ANSI C compiler
- Install Metaware ANSI C compiler
- Install GNU ANSI C compiler
- Install Saber C 2.0 C development environment
- Install CodeCenter 3.0 C development environment
- Install CodeCenter 4.0 C development environment
- Install Codecenter 4.1 C development environment

Windows and Graphics Installation

- Install and build X11R4 X Windows system
- Install and build X11R5 X Windows system

- Install and build public domain X Window programs from RTR software
- Install and build public domain X Window programs from Walnut Creek CD
- Install and build Portable BitMap image manipulation software
- Install XV X Windows image display system Version 2.21
- Install XV X Windows image display system Version 3.0
- Install UNIRAS agX/Toolmaster Version 6.3a libraries
- Install UNIRAS UNIGRAPH scientific visualization software
- Install UNIRAS agX/Toolmaster Version 6.3b libraries
- Install XtraWidgets widget library

General Tool Installations

- Install IslandWrite, IslandDraw, and IslandPaint (Version 3.0)
- Install WordPerfect 5.1
- Develop window printing script files (windowprint, rectprint, etc.)

Review of Technologies

The review of current computer technologies to support the development of a cooperative ecological simulation architecture required reading many books and manuals. In many cases example code sets were developed for testing and evaluation purposes.

X Windows and Graphics Display Systems

- The O'Reilly 9 volume X Windows series covering 6000 pages and several thousand functions and data structures.
- The Prentice Hall 5 volume OSF/Motif series covering 2500 pages and several hundred function calls and data structures.
- The SUN OpenWindows manual series covering several hundred pages, function calls, and data structures.
- Other texts on X Windows programming by Johnson & Reichard, Kobara, and Young.
- The UNIRAS 5 volume agX/Toolmaster manual series covering 3000 pages and over 400 function calls.

UNIX Inter-Process Communications

- UNIX Network Programming by W.R Stevens (762 p)
- Advanced Programming in the UNIX Environment by W.R. Stevens (744 p).
- UNIX Programmer's Reference by J.J. Valley (826 p)
- Numerous SUN Microsystems publications and manuals.

GIS Systems

- GRASS user Guides
- GRASS Programmers Guide
- ARC/INFO GRID and ARCPLOT manuals

Development of Code Libraries

The following code libraries were developed, tested, and documented to support construction of the Loki session manager, client program API, and shared maps.

Code Libraries			
Library	Description	Modules	Lines
Datum	Supports access from any datum type to any datum type with missing and default value support. Enables shared map access.	29	2814
Error Handler	Supports recording, storing, querying, and reporting errors in a stack.	23	886
Geo Reference	Supports map co-registration independent of map units and projection.	23	1073
Link List	Provides basic link list creation, insertion, deletion, and search support for all other libraries.	36	1822
LokiMap	Access and support for shared maps in their native format.	46	2618
MapModel	API functions to access LokiMap shared maps with datum and units independence.	58	2420
Parser	Text tokenizing and parsing.	30	1598
SimTime	Simulation time conversion and arithmetic.	17	649
Strings	Miscellaneous string functions.	3	101
Transect	Supports datum and type independent transect sampling of shared maps.	28	1805
Units	Supports automatic units conversion between native shared maps and client map views.	7	518
11	Totals	300	16,304

Development of the Prototype Loki System

In addition to the code libraries list above, a set of functions were developed and tested to implement the Loki session manager, a simple simulation client, and a map display client. These have been successfully run in a "proof of concept" trial.

In the proof of concept trial, one client program read a file in which weather sets appeared at random time intervals. The client then used a shared elevation map to distribute the temperature over the landscape. This landscape temperature map was then displayed in a graphics window by the map display client.

Visually, the weather data scrolled through a text window in the first client as new weather sets were read, and the landscape temperature map was dynamically updated. The proof of concept trial successfully demonstrated the Loki session manager control over two clients.

Collaboration With Colleagues

Work on this project has produced the following collaborations:

- Work with Richard C. Rothermel to develop an interactive electronic fire characteristics ("hauling") chart program. The program utilizes the UNIRAS agX/Toolmaster library to produce color charts suitable for publishing and overhead projection.
- Work with Ian French to simulate cellular fire spread in grid maps and graphically analyze distortion due to neighborhood effects.
- Discussions with Mark Finney on the integration of Huygens' Principle into fire perimeter modelling and the Loki system.
- Discussions with Robert E. Keane on the integration of stand succession and fire mortality modelling into the Loki system.

Papers and Conferences

- Fire Growth Simulation Model - An Element in the Integrated Fire Management System. P.A. Andrews and C.D.Bevins. 1992.
- Fire Growth Simulation for Prescribed Natural Fire. P.A. Andrews and C.D. Bevins. 1993.
- Fire and Meteorology Resource Spatial Analysis workshop. Feb 26-28, 1992. Tucson, AZ.
- SIGGRAPH 1992. Aug 1992. Chicago, IL.
- First Annual International MOTIF Users Meeting. Dec 8-11, 1991. Washington, DC.
- Second Annual International MOTIF Users Meeting. Nov 30 - Dec 2, 1992. Washington, DC.
- First International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling. Sep 15-19, 1991. Boulder, CO.
- Symposium on Fire in Wilderness and Park Management: Past lessons and Future Opportunities. Mar 30 - Apr 1, 1993. Missoula, MT.

- Second International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling. Sep 26-30, 1993. Breckenridge, CO.

- 12th Conference on Fire and Forest Meteorology. Oct 26-28. Jekyll Island, GA.

INT-90482-RJVA

Loki: Proof of Concept

November 1993

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Introduction

This paper reports on the achievement of "proof of concept" for the Loki software architecture for cooperative fire and ecosystem modeling.

The Loki Architecture

The Loki architecture allows multiple, separate, simulation models to communicate and cooperate in holistic, large scale simulations. The simulations run concurrently on UNIX workstation networks supporting the Network File System. The architecture fully supports the X Windows System graphical user interface and protocols and complies with POSIX standards.

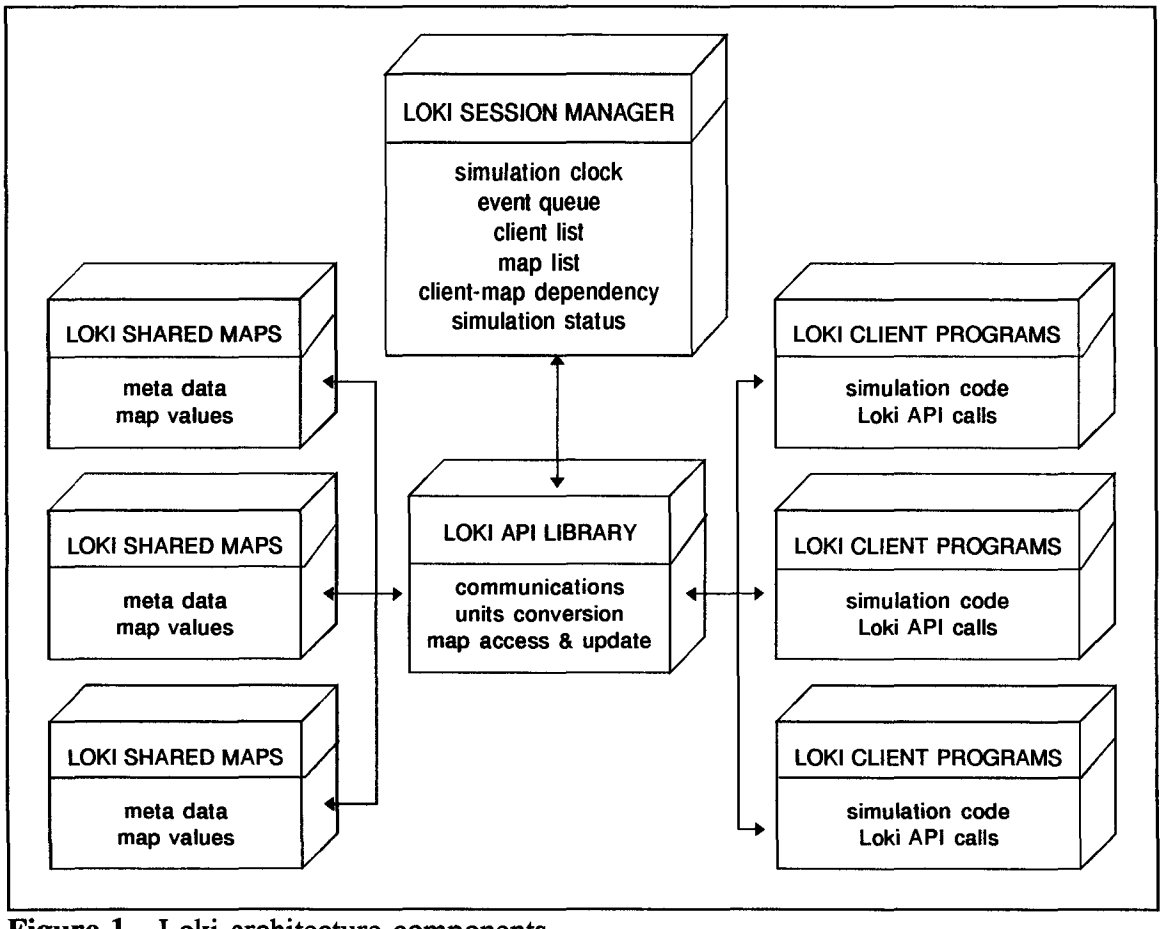


Figure 1 - Loki architecture components.

The Loki architecture consists of four components (figure 1): the session manager, the application programmers' interface (API) library, client programs, and shared map data.

The Loki session manager reads the simulation script, launches all the simulation models, and synchronizes communication between models. The simulation script specifies the geographic extent of the simulation, the maps and clients to use, and a preliminary set of simulation events (such as start and stop time). The session manager determines and resolves the client-map dependencies during the simulation, and notifies each client program whenever one or more of its input maps have changed so the client can update its output maps.

Each client runs as a separate process on the UNIX workstation network. The client is started by the session manager, which also tells it when to initialize itself (allocate data structures or open files), make a simulation update, complete a simulation, and terminate. The development of client programs is facilitated by the Loki API.

Each client informs the session manager as to the generic type of map data it reads and writes (e.g., "elevation" or "airtemp") using the Loki API. The client also uses API function calls to retrieve and update the specific map data, schedule callbacks, and perform units conversion, GIS format conversion, and time arithmetic.

Client programs exchange spatial information through shared maps. As one client updates an output map, the session manager notifies other clients that depend upon the same map as input to update their simulation or display. Map sharing is implemented through UNIX mapped memory facilities and the Network File System. While shared maps are in a Loki specific format, they are dynamically converted from, and back into, various supported GIS formats during the simulation.

Any number of maps map be displayed and dynamically updated on the console during the simulation. A fire growth model could, for example, have 3-dimensional terrain maps of fuel moisture, fire perimeter, and wind direction simultaneously displayed along with a hygro-thermograph and fire size strip chart. Loki currently uses the X Window System, OSF Motif, and UNIRAS agX/Toolmaster libraries for graphical output.

Finally, since Loki is based upon the X Window System, the entire architecture is event driven. Event driven simulation allows the simulation clock to jump from one simulation event to the next. The scheduling of events is left up to each client program to specify as appropriate. While a fire growth model may schedule cell ignitions every few seconds or minutes, a stand succession model may schedule a stand update only one a year or decade.

An event driven architecture also enables users to interact with the simulation through the keyboard or mouse, allowing for truly interactive modeling and gaming. User could, for example, start a bulldozer client, ignite a backfire, or modify fuels during a fire growth simulation.

Proof of Concept

Computer code for the session manager, API, and a set of demonstration clients has been successfully developed and tested. A live demonstration of these architecture elements working together in a cooperative simulation constitutes the proof of concept.

Inputs

A simulation script file (figure 2) defining the demonstration includes the following clients:

- "wxreader" reads a stream of weather observations occurring at random intervals and distributes the air temperature over the geographic area. It uses an "elevation" map as input, applies an adiabatic lapse rate to the temperature, and writes the results to an "airtemp" map.

- "view3d" is a general purpose 2- and 3-dimensional map display client. For this demonstration, it is invoked twice, once to display "airtemp" as a 2-d contour map, and again to display "airtemp" as a 4-d map draped over "elevation".

- "mapstats" is a general purpose map statistical summary and display client. It scans all the values of its input map and derives its mean, minimum, maximum, etc. Any statistic may then be displayed in a moving strip chart. The client is invoked twice, once to display the mean "airtemp" in a strip chart during the simulation, and once to display a "thermometer" of the mean airtemp.

- "depend" is a client program that simply forces an input-output dependency between two maps. In this case, a dummy "lastmap" is made dependent upon "airtemp". This makes "lastmap" the last map to be updated after every simulation event, queuing the "capture" client to take a screen snapshot.

- "capture" is a screen capture client. It takes a snapshot of the screen whenever "lastmap" is updated and converts the snapshot from Sun raster format into TIFF format, ready for transport to a slide film recorder.

Elevation data is taken from a 5 by 5 kilometer area of the Phlox Creek drainage inside Yellowstone National Park. The map is in GRASS4 ASCII format with values indicating 100 foot intervals. The map has a 50 meter resolution, resulting in a 100 by 100 cell area.

Weather data is read from a file containing 28 observations from Yellowstone National Park between 16:00 hours, August 25 and 16:00 hours, August 26, 1988. The simulation time span specified in the script file is from noon on August 25 through 16:00, August 26.

```
* Loki demonstration for Phlox Creek, YNP
*
* Define the geographic extent.
georef Meters 4897000 4892000 570000 565000
*
* Declare the maps
maplayer "elevation" FeetC100   elevation.asc Grass4Ascii
maplayer "airtemp"   fahrenheit airtemp.asc   Grass4Ascii
maplayer "lastmap"   fahrenheit airtemp.asc   Grass4Ascii
*
* Read and distribute the weather
client  wxreader -weather wx880825.dat
*
* airtemp: 2d contour map
client view3d -variable airtemp -style contourgrid -cellunits fahrenheit -mapunits
        meters -classes 41 -minimum 30. -maximum 100 -shade 1
*
* airtemp: 4d map draped over elevation
client  view3d -variable airtemp -style 3d -cellunits fahrenheit -mapunits meters
        -elevation -classes 41 -minimum 30. -maximum 100. -shade 1    -mesh 5
*
* airtemp: 3d map
*client  view3d -variable airtemp -style 3d -cellunits fahrenheit -mapunits meters
        -classes 41 -minimum 30 -maximum 100 -shade 1 -mesh 5
*
* airtemp: moving graph of mean
client  mapstats -variable airtemp -units fahrenheit -output mapstats.out -stat mean
        -chart graph -classes 41 -minimum 30 -maximum 100 -shade 1 -graph 10
*
* airtemp: thermometer
client  mapstats -variable airtemp -units fahrenheit -chart vbar -xspan 0.05 -yspan
        0.6
*
* Screen capture
client depend -input airtemp -output lastmap
client capture -variable lastmap -pause 1
*
event loki    start          1988/8/25 12:00:
event loki    pause           1988/8/25 12:00:0.1
event loki    pause           1988/8/25 16:50:
event loki    stop           1988/8/26 16:00:01
```

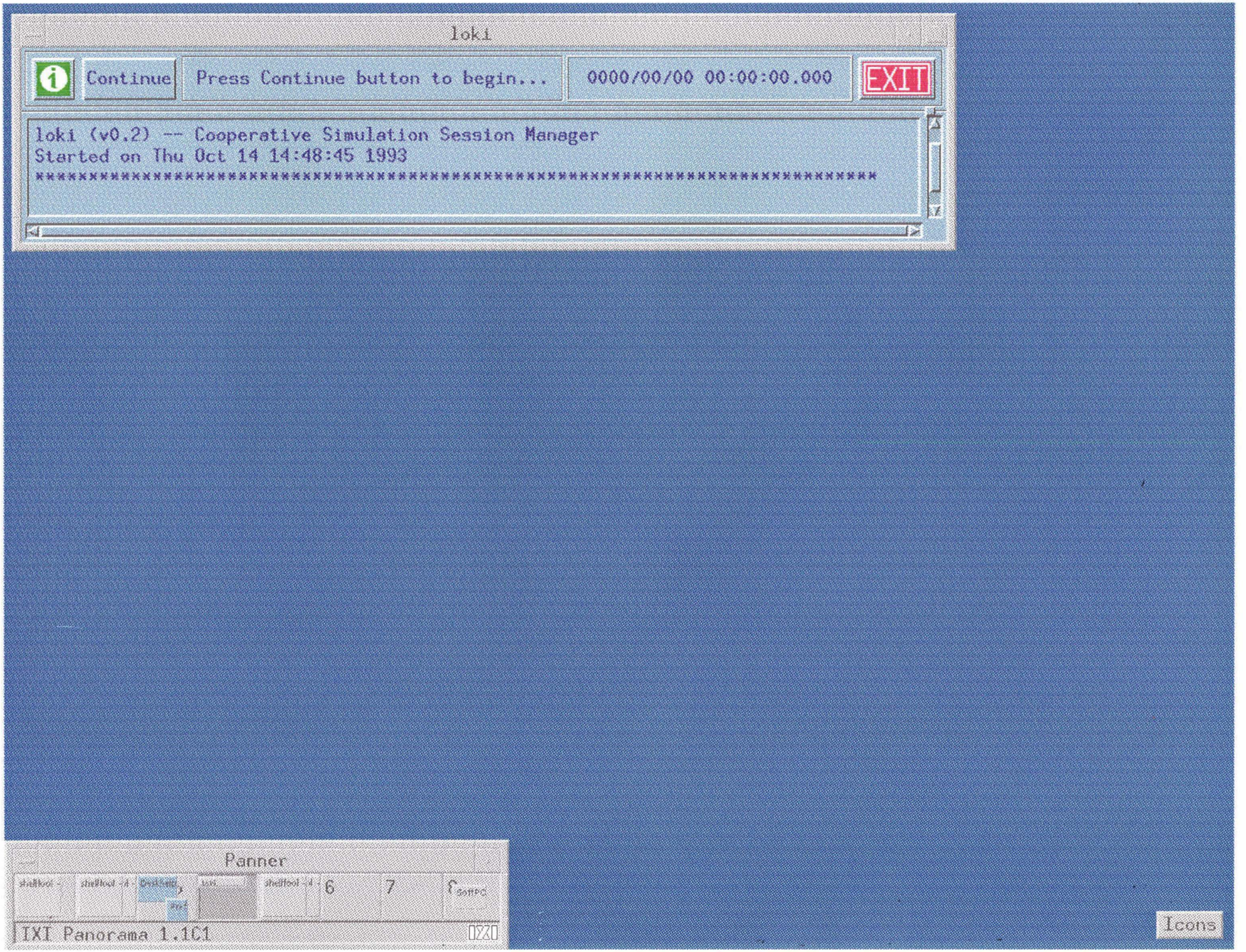
Figure 2 - Loki script file for the Phlox Creek "proof of concept" demonstration.

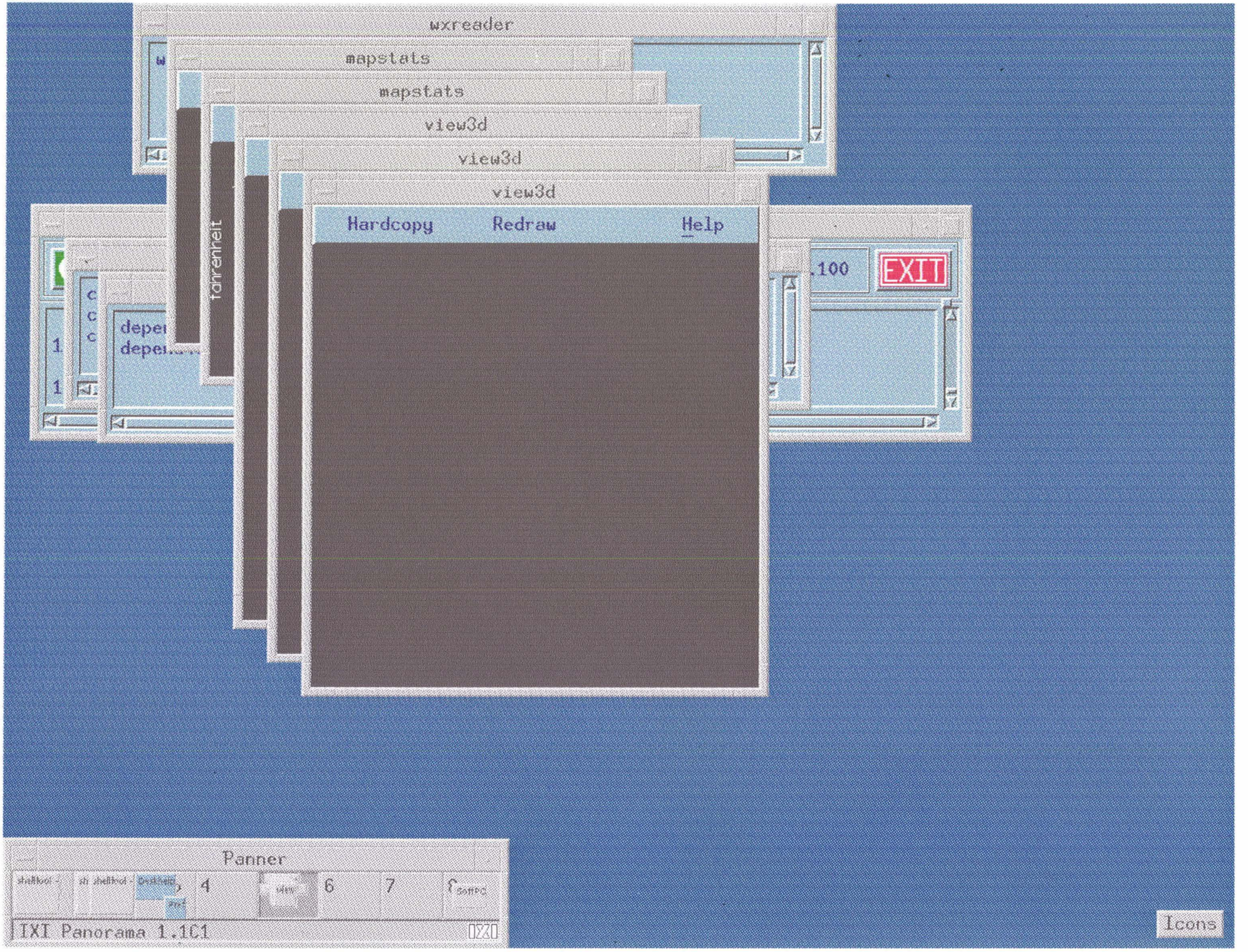
Results

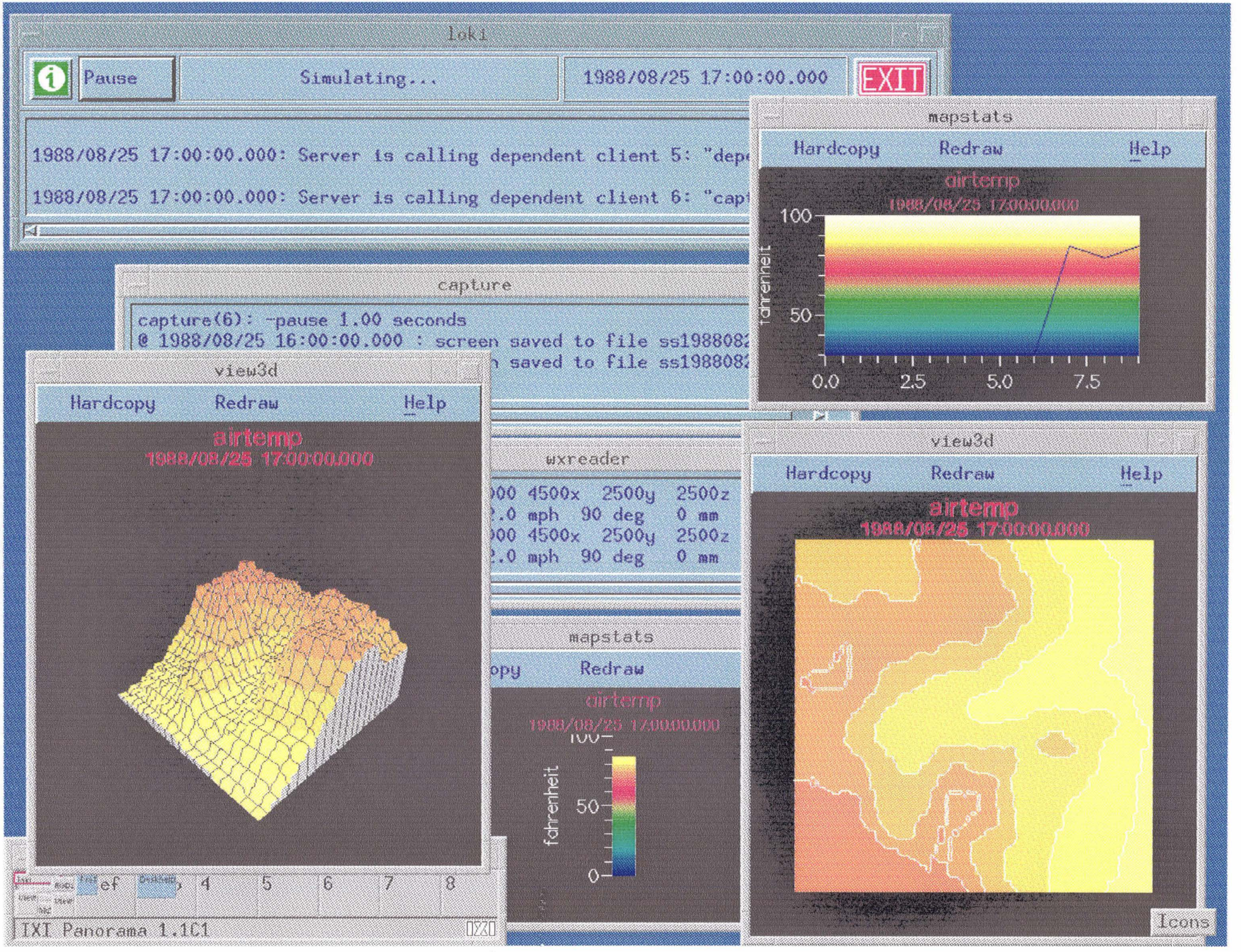
Figure 3 shows the console screen after invoking the Loki session manager. Notice that the session manager is an X Windows program with an OSF Motif graphical user interface. At this point, the program is waiting for the "Continue" button to be pressed before it starts processing the script file.

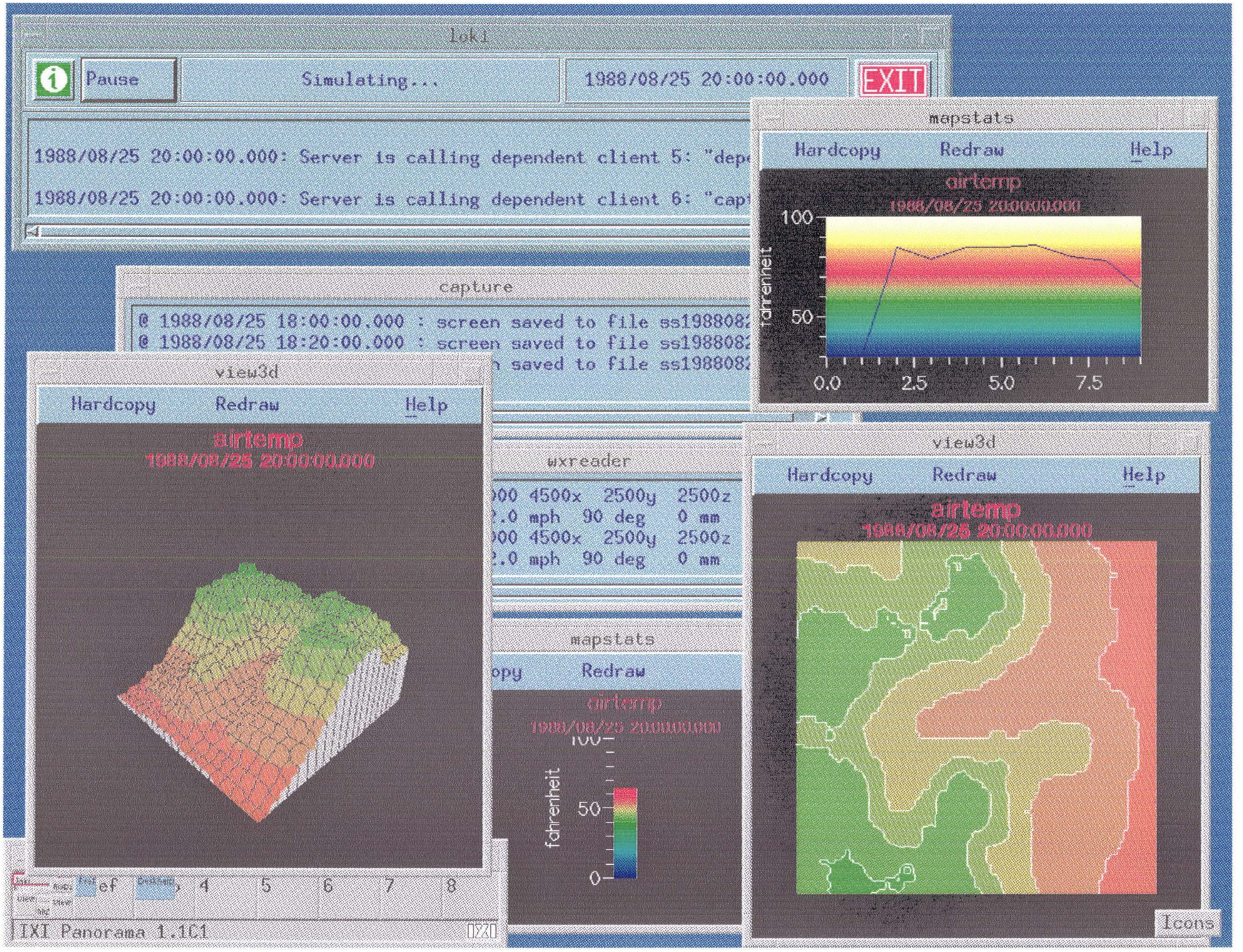
The session manager next reads, validates, and opens the map files specified in the script. It then launches each client program specified in the script. Figure 4 shows the console screen after all the clients have been launched. Since these are all stand alone X programs, their windows can be moved, resized, or converted into icons.

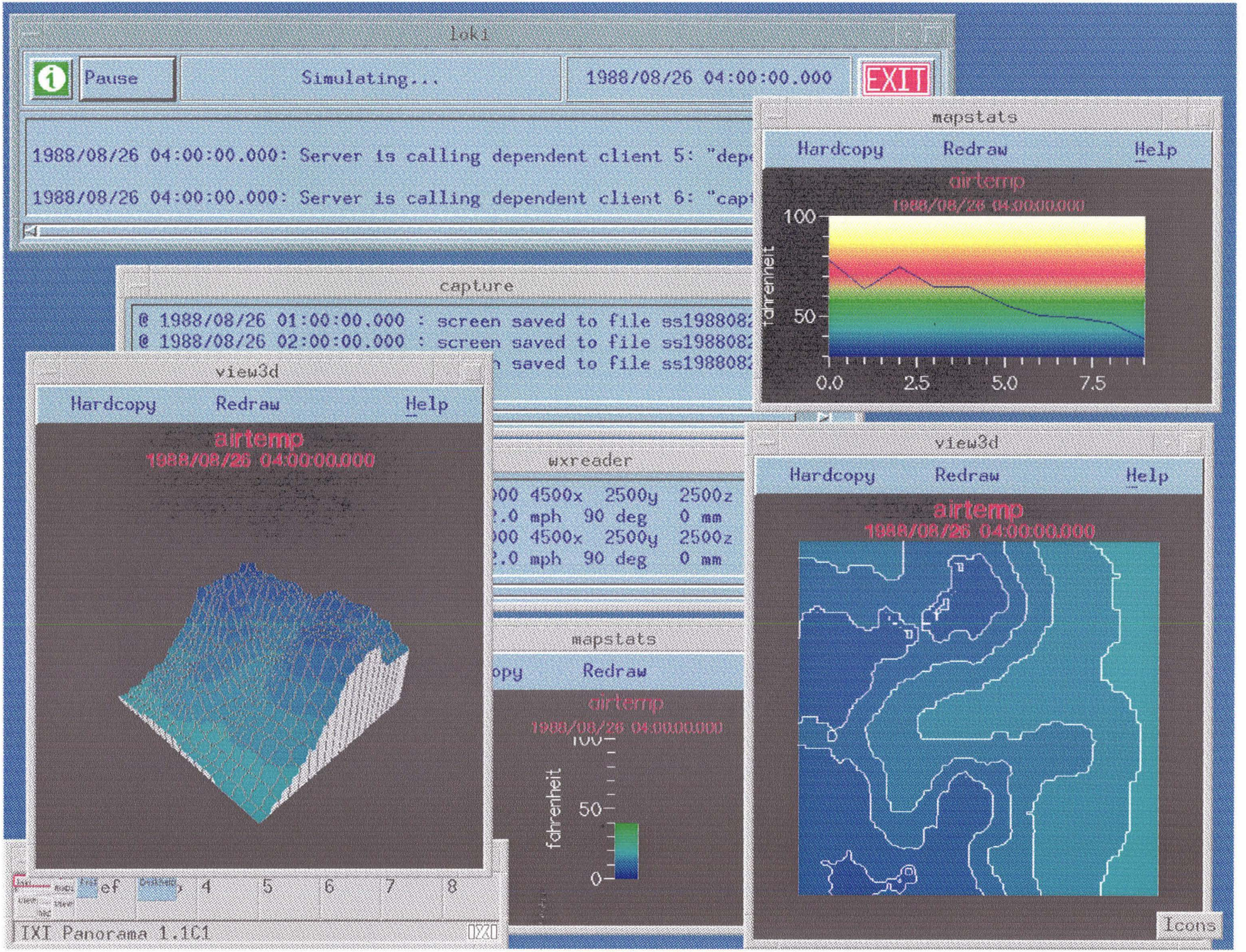
Figures 5 through 10 show the simulation at various points in time. Client access to shared map data is being synchronized by the session manager, client-map dependencies are being fully resolved during each event, and the display clients are dynamically updating their windows throughout the simulation.

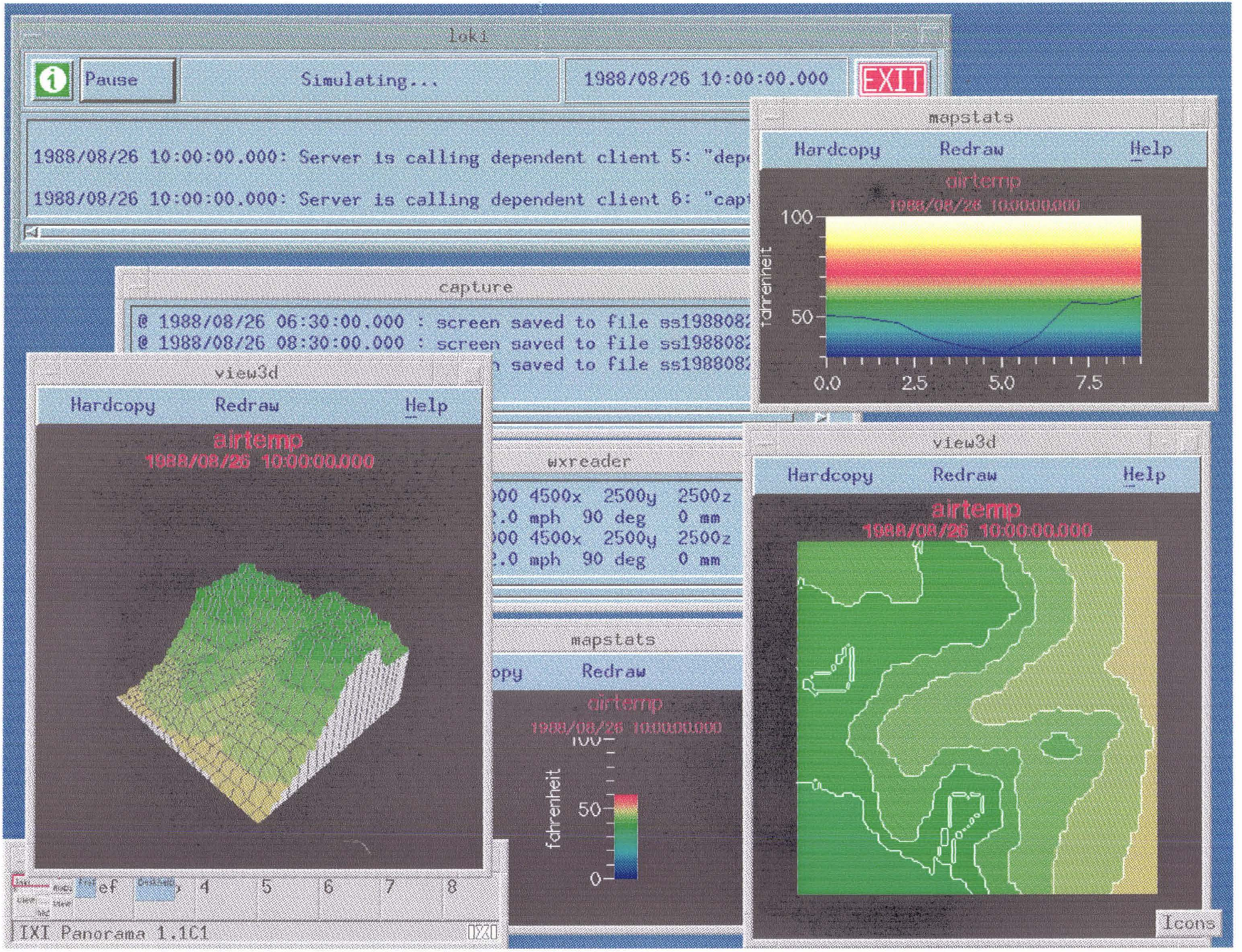

loki
Continue
Press Continue button to begin...
0000/00/00 00:00:00.000
EXIT
loki (v0.2) -- Cooperative Simulation Session Manager
Started on Thu Oct 14 14:48:45 1993
****
Panner
6
7
IXI Panorama 1.1C1
Icons


wxreader
mapstats
mapstats
view3d
view3d
view3d
Hardcopy
Redraw
Help
fahrenheit
.100
EXIT
Panner
4
6
7
IXI Panorama 1.1C1
Icons


loki
Pause
Simulating...
1988/08/25 17:00:00.000
EXIT
1988/08/25 17:00:00.000: Server is calling dependent client 5: "dep
1988/08/25 17:00:00.000: Server is calling dependent client 6: "cap
capture
capture(6): -pause 1.00 seconds
@ 1988/08/25 16:00:00.000 : screen saved to file ss198808
saved to file ss198808
mapstats
Hardcopy
Redraw
Help
airtemp
1988/08/25 17:00:00.000
100
50
fahrenheit
0.0
2.5
5.0
7.5
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/25 17:00:00.000
wxreader
000 4500x 2500y 2500z
.0 mph 90 deg 0 mm
000 4500x 2500y 2500z
.0 mph 90 deg 0 mm
mapstats
opy
Redraw
airtemp
1988/08/25 17:00:00.000
100
50
fahrenheit
0
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/25 17:00:00.000
ef
4
5
6
7
8
TXI Panorama 1.1C1
Icons


loki
Pause
Simulating...
1988/08/25 20:00:00.000
EXIT
1988/08/25 20:00:00.000: Server is calling dependent client 5: "dep
1988/08/25 20:00:00.000: Server is calling dependent client 6: "cap
capture
@ 1988/08/25 18:00:00.000 : screen saved to file ss198808
@ 1988/08/25 18:20:00.000 : screen saved to file ss198808
saved to file ss198808
mapstats
Hardcopy
Redraw
Help
airtemp
1988/08/25 20:00:00.000
100
50
fahrenheit
0.0
2.5
5.0
7.5
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/25 20:00:00.000
wxreader
00 4500x 2500y 2500z
.0 mph 90 deg 0 mm
00 4500x 2500y 2500z
.0 mph 90 deg 0 mm
mapstats
opy
Redraw
airtemp
1988/08/25 20:00:00.000
100
50
0
fahrenheit
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/25 20:00:00.000
ef
4
5
6
7
8
IXI Panorama 1.1C1
Icons


loki
Pause
Simulating...
1988/08/26 04:00:00.000
EXIT
1988/08/26 04:00:00.000: Server is calling dependent client 5: "dep
1988/08/26 04:00:00.000: Server is calling dependent client 6: "cap
mapstats
Hardcopy
Redraw
Help
airtemp
1988/08/26 04:00:00.000
100
50
fahrenheit
0.0
2.5
5.0
7.5
capture
@ 1988/08/26 01:00:00.000 : screen saved to file ss1988082
@ 1988/08/26 02:00:00.000 : screen saved to file ss1988082
saved to file ss1988082
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/26 04:00:00.000
wxreader
000 4500x 2500y 2500z
2.0 mph 90 deg 0 mm
000 4500x 2500y 2500z
2.0 mph 90 deg 0 mm
mapstats
opy
Redraw
airtemp
1988/08/26 04:00:00.000
100
50
fahrenheit
0
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/26 04:00:00.000
ef
4
5
6
7
8
IXI Panorama 1.1C1
IXI
Icons


loki
Pause
Simulating...
1988/08/26 10:00:00.000
EXIT
1988/08/26 10:00:00.000: Server is calling dependent client 5: "dep
1988/08/26 10:00:00.000: Server is calling dependent client 6: "capt
capture
@ 1988/08/26 06:30:00.000 : screen saved to file ss198808
@ 1988/08/26 08:30:00.000 : screen saved to file ss198808
saved to file ss198808
mapstats
Hardcopy
Redraw
Help
airtemp
1988/08/26 10:00:00.000
100
50
fahrenheit
0.0
2.5
5.0
7.5
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/26 10:00:00.000
wxreader
000 4500x 2500y 2500z
.0 mph 90 deg 0 mm
000 4500x 2500y 2500z
.0 mph 90 deg 0 mm
mapstats
opy
Redraw
airtemp
1988/08/26 10:00:00.000
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50
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Redraw
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airtemp
1988/08/26 10:00:00.000
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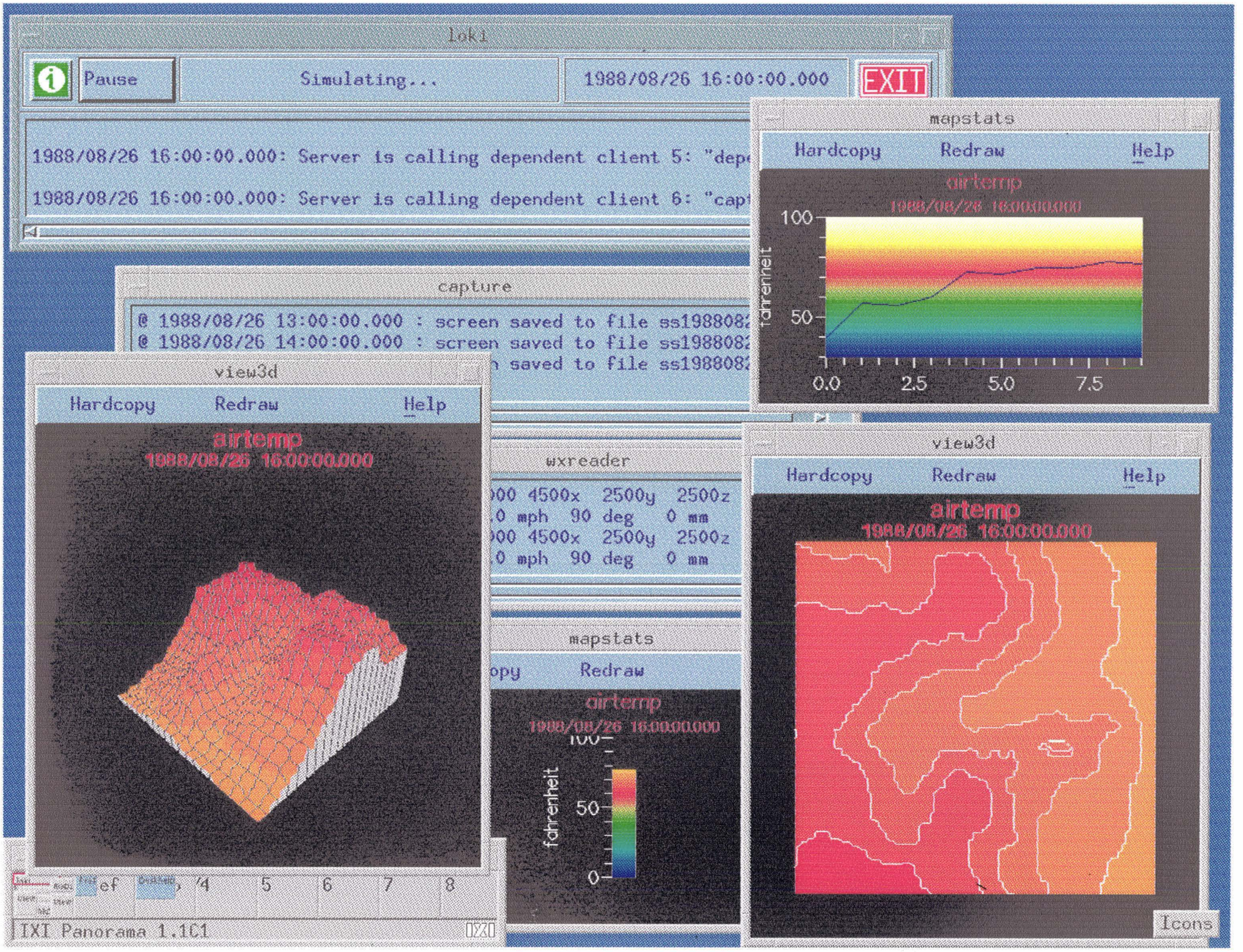
IXI Panorama 1.1C1
Icons


loki
Pause
Simulating...
1988/08/26 16:00:00.000
EXIT
1988/08/26 16:00:00.000: Server is calling dependent client 5: "dep
1988/08/26 16:00:00.000: Server is calling dependent client 6: "cap
capture
@ 1988/08/26 13:00:00.000 : screen saved to file ss198808
@ 1988/08/26 14:00:00.000 : screen saved to file ss198808
saved to file ss198808
mapstats
Hardcopy
Redraw
Help
airtemp
1988/08/26 16:00:00.000
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7.5
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4500x 2500y 2500z
mph 90 deg 0 mm
4500x 2500y 2500z
mph 90 deg 0 mm
mapstats
Redraw
airtemp
1988/08/26 16:00:00.000
100
50
0
fahrenheit
view3d
Hardcopy
Redraw
Help
airtemp
1988/08/26 16:00:00.000
Icons
IXI Panorama 1.1C1

Fire Growth Simulation Model–
An Element in the Integrated Fire Management System

Progress Report
February 1992

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Collin D. Bevins
Systems for Environmental Management
Missoula, MT

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Fire Growth Simulation Model— An Element in the Integrated Fire Management System

Patricia L. Andrews
February 1992

The Fire Behavior Research Work Unit is developing a fire management system to meet the full range of fire management needs. That does not mean that we will write one huge computer program that will do everything for everyone. It does mean that we will consider the full range of fire management needs and propose a method of cooperation to develop systems to meet those needs.

An attached paper "Fire Behavior System for the Full Range of Fire Management Needs" (Rothermel and Andrews 1987) discusses the need for an integrated fire management system and approaches to achieving the goal. Future systems will certainly take advantage of available technology, like Geographic Information Systems (GIS). But they will also be based on improved fire behavior models. Much of the research being done by the fire behavior RWU is aimed at improving those models.

The attached paper "A Common Approach to Fire Behavior, Fire Danger, and Fire Management Systems" (Andrews, in press) discusses potential cooperation between the U.S. and Canada and possibly Australia in developing the next generation system.

An important part of the integrated system will be a fire growth simulation model. It will be used for applications from training, to real-time fire behavior prediction, to planning. An attached paper "Application of Fire Growth Simulation Models in Fire Management" (Andrews 1989) discusses considerations in designing a simulation to meet the range of needs.

One of the problems with the current state of fire management systems is that programs were developed independently to meet specific needs. Developing separate fire growth simulation models to meet various needs would just add to the confusion. We worked on developing a simulation to the point that we saw the potential and also the problems. We are now working on "LOKI: An Architecture for Cooperative Simulation Modelling" as described by Bevins in the following section.

LOKI will facilitate cooperation among researchers and systems developers who work on various aspects of the simulation. Note that the users that Bevins refers to are those people. Fire managers who use the final product will not be aware of LOKI.

LOKI: An Architecture for Cooperative Simulation Modelling

Collin D. Bevins
Systems for Environmental Management
February 1992

The Problem

Developers of ecosystem simulation models face several obstacles in the design and maintenance of their programs. As computer hardware becomes less expensive and more powerful, ecosystem simulations become more complex and holistic. The increased complexity underscores problems and questions historically faced by model developers:

- How should simulation models interface with geographic information systems (gis)? How does a model read, modify, and update map data from the gis, and how are maps displayed during the simulation? The appropriate solution depends in large part upon whether simulation models are viewed as operations within a gis, or the gis is treated as a data base and display client of the simulation.

- How should the voluminous source code needed for complex simulations be designed and maintained? Simulation models are especially prone to continued refinement and debugging. As better and broader simulation components are added, what is the best method for reducing the chances of introducing new errors into the system?

- How can a single development center incorporate models from other disciplines or outside institutions to create holistic simulations?

- Once a simulation system is developed, how is it best modified and adapted for evolutionary uses including (1) testing of the simulation itself, (2) research on the ecosystem processes being simulated, (3) educational demonstrations, and (4) interactive user training? How can a research model be most easily modified to, for example, accept user interaction during the simulation, turning it into a training simulation?

- How can users easily reconfigure a complex simulation to (1) test alternative simulation components within a holistic system and (2) design alternative holistic simulation systems?

- How can ecosystem simulations take best advantage of current and future computer architectures including multi-processing workstations, local area networks, distributed processing, object-oriented design, and graphical user interfaces?

A Solution

LOKI is a set software programs and rules for writing concise, independent simulation models that cooperate with one another in larger, holistic simulation systems.

The LOKI software distribution includes **xloki**, the simulation manager program. The "rules" are embedded in an application programming interface (API) library used by developers when writing LOKI-compliant simulation programs. The LOKI distribution also includes supporting utility programs and any contributed simulation programs.

Each concise simulation model is a separate computer process that simultaneously runs in the background with all the other models needed for a holistic simulation. The user specifies which simulation models to run and which gis maps to access in an **xloki** input file. Changing the configuration of a holistic simulation is simply a matter of changing the input file; **xloki** provides all the model invocation, communication, and synchronization services, as well as map access, registration, re-sampling, units conversion, and display services required by the separate simulation processes.

Each simulation program has limited scope; it gets its map data from one or more map matrices provided by the API (and any other supporting data sources as needed), performs its computations on the arrays, and hands the results back to the API for storage. The program does not have to deal with data locations, formats, or units of measure; that is handled by the LOKI API.

After a simulation model is started by **xloki**, it "sleeps" in the background, waiting for a "wake up" call from **xloki**. The call may arrive as a result of a scheduled event or because one of the model's input maps has been updated.

xloki maintains a simulation clock and an event queue to schedule wake up calls among all the simulation models. Whenever a model is awakened, it may reschedule another wake up call for a later time.

xloki works through its event queue to find the next simulation date, time, and process. Since a fixed time step is not used, **xloki** efficiently processes simulation configurations mixing models running at millisecond resolution with those operating at a forest succession time scale.

When **xloki** finds the next scheduled event, it examines the simulation model - map layer dependencies and dynamically creates a model calling hierarchy starting with the scheduled model. The hierarchy ensures that all necessary models are awakened in the appropriate order to achieve a steady state within the map data at the end of the event.

LOKI-compliant simulation models are developed using the LOKI API and the X Window system libraries. Since the programs are event driven, they can be written to accept user interaction during the simulation from the keyboard and/or mouse.

Benefits of the LOKI Architecture

- Simulation models are easier to write and maintain because (1) they are smaller and limited in scope, (2) all map data access, registration, updating, and units conversion are handled by LOKI API functions, and (3) all gis interface and map display functionality may be off-loaded to other **xloki** clients.

- Users easily assemble and re-arrange alternative holistic simulation systems in a tinker toy fashion from a toolbox of modular simulation models.

- As the benefits of LOKI become apparent, the availability of contributed public domain simulation components should increase, broadening the choice of models from, for example, geological, meteorological, hydrological, and biological disciplines.

- Map data layers may be dynamically updated and displayed in 2 or 3 dimensions, and manipulated by end user(s) during the simulation.

- Map data may be saved at regular simulation time intervals (or only when updated) for later display and analysis by the gis.

- All LOKI programs use the X Windows libraries, the graphical user interface standard for POSIX systems, and may run across heterogenous computer networks.

- All simulation models run simultaneously in the background, and therefore may be distributed across a computer network.

- **xloki** dynamically resolves the model calling hierarchy during each simulation time step, waking simultaneously all the processes at a given level in the hierarchy, and therefore taking advantage of distributed or multi-processor architectures.

- LOKI programs are event-driven so simulations may be written to accept user input from the keyboard and mouse.

- Map data are transparently read from and written to various supported gis formats, allowing users to integrate simulation models with their existing gis.

In summary, LOKI provides an architecture to (1) ease simulation program design, maintenance, and refinement, (2) maximize end user flexibility in simulation system configuration, (3) promote the transition of simulations models through the research, education, and training phases and (4) efficiently use current and future computer technology.

Background and Status

The LOKI architecture and software is under cooperative development by the Fire Behavior Research Work Unit, Intermountain Fire Sciences Lab, USDA Forest Service, and Systems for Environmental Management, both of Missoula, MT.

We began work on the LOKI concept in August 1991 as a result of attempting to refine and expand fire growth simulation models, only to be plagued by the problems already stated. We wanted to add functionality from other disciplines and organizations into the model (forest succession, smoke production, etc.), refine and test alternative algorithms developed in-house (fire spread, fuel moisture, etc.), become less dependent upon a single gis, create versions suitable for research, education, and/or training, and take advantage of expanding hardware, networking, and GUI capabilities.

We felt if the concepts of modular and object oriented programming could be abstracted to a higher level, e.g. the operating system level, all these tasks would be simplified. Multi-tasking POSIX-compliant computer systems allow us to run multiple simulations concurrently. The X Windows system provides the necessary communications and synchronization protocols and a standard graphical user interface.

The ultimate goal is to provide a LOKI software distribution containing:

- **xloki**, the simulation manager,
- **xmapload**, a program used by **xloki** to read, register, re-sample, and convert data from supported gis's,
- **xmapview**, a program to display and dynamically update map data in 2 or 3 dimensions during the simulation,
- **xmapsave**, a program to convert LOKI map data layers into supported gis formats,
- the **LOKI API** containing all functions needed to develop a LOKI-compliant simulation model, and
- a collection of simulation models and templates donated to the LOKI software distribution by ourselves and other developers.

Summary of the LOKI Cooperative Simulation Architecture

LOKI Objectives

- Simplify the implementation and application of complex holistic ecosystem simulations from the simulation users' viewpoint.
- Simplify the design, development, and maintenance of complex ecosystem simulations from the application developers' viewpoint.
- Provide simulation models an evolutionary pathway from research into the demonstration, education, management, and training domains.
- Provide a transparent method of integrating gis data sources and ecosystem simulations.

Basic Concepts

- A "holistic" simulation is a collection of concise, independent simulation modules running within a common geographic context.
- Each module focuses on a discrete ecosystem process.
- Each module runs as a separate computer process (e.g., task or job) on the network.
- Modules communicate with, and are coordinated by, the simulation manager program **xloki**.
- Modules read from and write to shared map data.
- Map data are dynamically sampled from supported gis formats into the geographic context.
- The simulation is event-driven, with modules responding to changes in their input map data.

LOKI Software Distribution Components

- "xloki" manages the holistic simulation, providing simulation clock, event queue, synchronization, and units conversion services.
- "xmapload" is called by xloki to read, register, re-sample, and convert data from supported gis's.
- "xmapview" displays and dynamically updates map data 2 or 3 dimensions during a simulation Multiple instances of xmapview may be running during a simulation.
- "xmapsave" converts LOKI map data into supported gis formats.
- The LOKI API, a small library of C-callable functions needed to create LOKI-aware simulation modules.
- A collection of simulation modules and templates donated to the LOKI software distribution by ourselves and other participants.

Simulation Capabilities

- Map data are dynamically re-sampled and converted to/from supported native gis formats without user intervention.
- Users may view, rotate, and scale dynamic map data in 2D or 3D during a simulation.
- Simulations may accept user input from the keyboard or mouse to dynamically alter map data during a simulation.
- Maps may be saved at specified intervals (or whenever updated) for later display and analysis within a gis.

Benefits to the Simulation User

- Easily create complex holistic ecosystem simulations from sets of cooperating LOKI-aware modules.
- Incorporate modules developed by other organizations or context experts.
- Easily test alternative modules within a simulation scenario.
- Easily develop alternative holistic simulation scenarios.

Benefits to Simulation Programmers

- Use of standard X windows libraries and widget sets is encouraged.
- LOKI API hides all map data sources, formats, data types, and units.
- LOKI API hides all communication and synchronization tasks.
- LOKI API hides all module dependency determinations.
- Programmer can focus on coding the simulation algorithms.
- Modules are smaller and easier to design, debug, and maintain.

Technological Benefits

- Adheres to the POSIX.1 standard.
- Uses X Windows communication and display protocols.
- Able to distribute module execution across a heterogenous network.
- Efficiently utilizes advanced multiple-processor architectures.

Gen. Tech. Rep. PSW-101 Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1987.

Fire Behavior System for the Full Range of Fire Management Needs[1]

Richard C. Rothermel and Patricia L. Andrews[2]

Abstract: An "integrated fire behavior/fire danger rating system" should be "seamless" to avoid requiring choices among alternate, independent systems. Descriptions of fuel moisture, fuels, and fire behavior should be standardized, permitting information to flow easily through the spectrum of fire management needs. The level of resolution depends on the application, but the same central processor can be used. Three tasks must be carried out to reach the goal: (1) determination of fire management needs, (2) development of a central processor to be used as the core of the system, and (3) development of the individual subsystems with a framework for moving between them.

One of nine research initiatives proposed by the director of Forest Fire and Atmospheric Sciences Research staff in the Forest Service's Washington office is an "Integrated Fire Behavior/Fire Danger Rating System" (Philpot 1985). The initiative states: "A single, integrated system that can accommodate the full continuum of spatial/temporal resolution requirements--from National, long-range fire severity forecasting to real-time suppression strategy decisions on actual fires--is needed to meet the varying fire behavior information needs of wildland managers."

The need for an integrated fire behavior system designed for the full range of fire management needs has come about for several reasons:

1. Proliferation of systems based on fire behavior has resulted in confusion in the choice of the appropriate system for a specific fire management need.
2. It is difficult to make the transition from one system to another when moving from the planning to operational phases.
3. Requirements placed on fire managers for analysis and planning are much more demanding than in the early 1970's when the current fire behavior and fire danger systems were formulated. We expect this trend to continue.
4. There have been significant advances in fire research.
5. The technology available for reaching fire managers and assisting them is increasing dramatically.

A fundamental concept of the system envisioned in the initiative is that it be "seamless," or integrated, to avoid requiring choices among alternate, independent systems. Descriptions of fuel moisture, fuels, and fire behavior should be standardized, permitting information to flow easily through the spectrum of fire management needs.

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We see three tasks as necessary to carry out the initiative:

Task 1. Determine the needs of fire managers for systems centered around fire behavior. Develop a plan that specifies the necessary subsystems, such as long-range planning, prescribed fire planning, fire danger rating, and dispatch. The plan should outline the span of operations for each subsystem with emphasis on their interaction.

Task 2. Develop a central processor containing the mathematical fire behavior prediction models that will serve as the core for all subsystems.

Task 3. Develop the subsystems using the new central fire behavior processor according to the plan defined in task 1. Develop a framework for accessing subsystems and moving between them.

The first two tasks can be carried out in parallel. There is a long lead time and there will be ample time for coordination. Planning for the third task can begin when the subsystems are identified, but actual development of the subsystems will depend upon completion of the central processor.

Developing a plan for the systems needed by operating agencies (task 1) should be the responsibility of those agencies with support from research. Developing a central processor for the systems identified in the plan (task 2) should be the responsibility of research with support from the operating agencies. Responsibility for developing the subsystems (task 3) will probably fall upon both research and the operating agencies. This third task is several years away.

NEED FOR THE INITIATIVE

Number of Systems/Confusion in Application

Since 1972, many systems have been developed to meet the expanding needs of fire management. Although fire behavior and fire danger rating are specifically mentioned in the title of the initiative, those are only two of the systems involved. Another system that is used nationwide by the Forest Service is the National Fire Management Analysis System (NFMAS) (USDA Forest Service 1983). Other examples are FIRECAST (Cohen 1986), RXWTHR and RXBURN (Bradshaw and Fischer 1981), HAZARD (Brown and others 1977), the National Fuel Appraisal Process (Radloff and others 1982), and the Initial Attack Management System (IAMS) (German 1985).

The National Fire Danger Rating System (Deeming and others 1977) was designed as a prefire planning tool. It is basically a seasonal weather processor. The indexes it produces are relative values that rate fire danger over broad geographic areas.

The fire behavior prediction system (FBPS) is based on concepts described by Rothermel (1983). It was designed to predict actual fire behavior and allows the user to tailor the resolution of the input to meet the application. The FBPS is available through a number of computing methods as summarized by Andrews (1986a). One of the most widely used methods is the BEHAVE fire behavior prediction and fuel modeling system (Andrews 1986b, Burgan and Rothermel 1984).

NFMAS is used to evaluate long-term consequences of alternative fire protection programs for relatively large planning units. It is essentially a hybrid of NFDRS and FBPS. NFMAS uses the danger rating equations and fuel models. However, it uses site-specific input and interprets output in terms of actual fire behavior.

In addition to national systems, individual administrative units have designed their own systems for assisting them in both long-term planning and day-to-day operations. A specific example is the Mt. Hood Field Guide for Appropriate Suppression Response (USDA Forest Service 1985). It is based on tables of predictions generated by BEHAVE.

It is understandable that there is confusion on proper application of the many fire management systems. However, there is a positive aspect to the large number of systems based on fire behavior. The utility of deterministic mathematical models structured into decision processing systems

has proved to be a highly effective and readily adaptable method of assessing fire management problems.

Difficult Transitions

Almost all current fire management systems are based on a mathematical model designed to predict the spread of a steady-state surface fire (Rothermel 1972, Albini 1976). There are, however, significant differences in the equations as they are used in NFDRS. Developers of other systems (e.g., NFMAS) have had to decide which set of equations to use. The difficult transition from one system to the next is caused by the difference in equations (the central processor).

The most visible aspect of this problem is the fact that there are two sets of fuel models. Fuel models are designed to work with a specific set of equations. If a fuel map is produced for use by NFMAS, it has NFDRS fuel models, and cannot be easily used for fire behavior prediction applications.

Changing Needs

If the National Fire Danger Rating System and the Fire Behavior Prediction System satisfied all of the needs of fire managers, there would not be the need for the initiative. Fire management, however, has become more complex since those systems were developed. The following are examples of the changing needs of fire managers:

--Managers now have options other than strict fire control. Unplanned ignitions may be declared prescribed fires rather than wildfires if they meet criteria set up in a fire management plan. In addition, there are options on the level of suppression action that might be taken on a wildfire; in Forest Service terminology, Contain/Confine/Control.

--Smoke production is becoming an overriding concern in connection with prescribed fire. The window of acceptable burning conditions may be quite narrow, making it critical that an acceptable day not be missed.

--Restricted budgets make it important that correct decisions be made on fuel treatment options using the best information available on expected consequences.

--The encroachment of homes into forest areas is causing a major problem for forest protection agencies.

--Prescribed fire is much more than the attainment of "black acres." More emphasis is being put on fire effects.

--Fire is just one aspect of the total resource management job and is becoming more integrated into the overall planning process.

--Forest managers often have duties that include more than fire. Fire behavior systems that are compatible and easy to use can help them make the best use of their time and help assure careful consideration of options without excessive tedium.

Available Research

Even if there were no compatibility problems with the current systems, it is time to begin planning a major change. The existing fire spread model is 15 years old and should be updated. Models are also needed for crown fires and smoldering ground fires. Other models are needed to supply inputs to these new fire models.

Advances in Technology

A trend that is most likely to continue and one that will have a large effect on the form of our product is the explosive advancement of technology. When the current fire danger rating and fire behavior prediction systems were developed, they were offered on mainframe computers using punch cards, and as publications of tables and nomograms. We have since progressed to using interactive programs on in-house computers, desk-top computers, and micro chips developed for handheld calculators. New systems will be able to take advantage of satellite mapping of fuels for large areas, geographic information systems, graphic output of results, telecommunications linking all levels of management, personal computers, and far more.

DEVELOPMENT OF THE CENTRAL PROCESSOR

The structure of a system is based on a flow of information from inputs through the

central processor to outputs. It is the fire behavior models and their related input and output models that we refer to as the central processor. This basic structure is altered to meet specific management needs by specifying methods for obtaining inputs required for certain operations. Inputs for planning may come from historical data bases, while real-time fire prediction requires up-to-the-minute data. Similarly, output is tailored for certain applications. This may involve maps that display levels of fire danger or suppression cost-plus-net-value-change analysis.

The use of mathematical models to predict fire behavior, fuel moisture, etc., has proved to be such a powerful technique and adaptable to so many fire management activities that the development of these models will continue to be the primary goal of our research.

Our knowledge of fundamental fire behavior and the factors controlling fire is still limited. A long list of items needing attention can be made quickly. Among the more challenging in the list are the nonuniform fuel problem, crowning, spotting, combustion of living fuels, burnout of large fuels, smoke production, and wind flow in rough terrain. Research results are available on some of these problems and research must continue, particularly in regard to arriving at general solutions that can be adopted in national systems.

Development of the central processor is not expected to be a crash program. The research emphasis for the next 3 to 5 years will be on fundamental research and model development. Because there are so many areas needing investigation and because of limited scientific staff, we must concentrate on the areas of highest priority.

Crown Fires and Spotting

Crown fires have aroused renewed interest. The Canadians have incorporated good field data in their system for quantitative fire behavior prediction (Lawson and others 1985). Albini (1986) made a strong effort at modeling the spread of crown fires, but the model is far from being ready for field application. We currently think that the biggest question is whether a surface fire will develop into a crown fire, i.e., identifying the conditions for the onset of crowning. Van Wagner (1977) has characterized the types of crown fires and their dependence on the surface fire. We believe that a detailed examination of the ignition-moisture relationship, especially as influenced by drought, needs further explanation.

Spotting is not restricted to crown fires, but is usually associated with severe fires of some type. It is one of the most intractable problems we face. Methods for predicting the distance firebrands will travel and still be burning are already in use (Albini 1979, Albini 1981, Albini 1983, Chase 1984). However, the ability to estimate the number of spot fires actually started remains a difficult problem.

Surface Fire Model

Research under way for several years is designed to increase our capability for predicting the behavior of fire in surface fuels. One of these efforts has been to define the limits of combustion. Better information about the probability of whether a fire will be sustained in a steady state condition is vitally needed. This research, begun originally to define the moisture of extinction, has gone well beyond that and will form the basis of a new fire spread model. It is being couched in stochastic form so that the probability of fire spread can be defined (Wilson, in press). The concepts have been developed using data from a much wider range of fuel sizes and loading conditions than were used in the original fire spread model. The research must be expanded to include the effect of wind, slope, and green fuels.

Significant progress has also been made in the area of fuel chemistry. We now have analytical instrumentation capable of determining the heat required to bring fuel up to ignition and for determining the heat available from both flaming and glowing combustion (Susott 1981). This information will form the basis for all new combustion models. We have a considerable amount of data, and a library of fuel particle properties is being developed.

Ground Fires

We need the characterization of smoldering in forest duff to estimate fire effects, the probability of holdover fires, and the probability of detection. Ground fires often occur in highly compacted fuel for which the surface fire spread model is not suited.

In addition to field work on duff consumption (Sandberg 1980, Brown and others 1985) a carefully designed laboratory study (Frandsen 1980) is closely examining combustion of duff and will provide the basis for models of the phenomenon.

Related Models

Input to the ground, surface, and crown fire models will often be the output of other mathematical models. Fuel moisture and fuel models are examples.

Although fuel moisture is sometimes determined from direct sampling and drying, it is more often calculated. Some recent significant results (Anderson 1985) indicate that we will probably have to abandon the idea that all fine fuels have 1-hour time constants for moisture response.

Description of the fuel geometry and load as an input to the surface fire spread model is currently put in terms of a fuel model. The fact that there are two sets of fuel models, 13 for FBPS and 20 for NFDRS, has caused considerable confusion. The spread model works under the assumption that fuels are uniform and continuous. In the field, however, that is the exception rather than the rule. The contribution of large fuels to fire problems must be included in future models and systems. In addition, we will have to learn to describe fuel for the ground and crown fire models as well as surface fires. The whole fuel issue needs to be reexamined closely and a fresh approach actively pursued.

SYSTEMS DEVELOPMENT

Simultaneously with work by research on the central processor, the operating units should be examining their needs and developing specifications for the systems envisioned for the future. Good coordination should be maintained between research and the operating agencies to assure realistic goals. One step in examining fire management needs should be a survey of applications that are based on the current fire spread model and definition of the needs they fill.

Careful consideration should also be given to an overall framework to tie the subsystems together. It is not expected that one computer program would contain all of the subsystems; it would be too large and unwieldy. A user-friendly interactive computer system using expert system techniques may help fire managers identify and access the subsystem appropriate to specific needs.

Although the equations in the new central processor may be more complex than those in current systems, the complexities will be invisible to the user. At present, much energy is put into explaining the differences in the central processors and fuel models of the NFDRS and FBPS. Basing all subsystems on the same central processor will eliminate this problem. In addition, the system of the future will be easier to use and understand due to more user-friendly interfaces, interactive exchange between the computer and the fire manager, and presentation of results in graphic formats.

SUMMARY

It is time to look at an integrated fire behavior/fire danger rating system that can meet the whole range of fire management needs. The large number of systems in use sometimes leads to confusion in proper selection and application. It is often difficult to make the transition from one system to another. The situation could be simplified by basing all subsystems of the integrated system on the same central processor and by providing a framework for accessing subsystems.

Development of the mathematical models that go into the central processor will be the primary responsibility of research. Operational agencies should take the lead in assessing needs and in developing a plan that specifies the necessary subsystems to fill those needs. This work will require careful coordination among researchers, system developers, and fire managers to

ensure that the system meets fire management needs of the future.

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Presented at Northwest Fire
Council and Western Forestry
and Conservation Association
Joint Annual Meeting, 1991
December 3-6, Victoria, BC

A Common Approach to Fire Danger, Fire Behavior, and Fire Management Systems

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ABSTRACT: The United States, Canada, and Australia have identified the need to find a common approach to fire danger, fire behavior, and fire management systems. Cooperative research under way will result in a new fire model based on both laboratory and field fire data. An integrated fire management system can be defined in terms of common building blocks (data and models) that can be structured for specific fire management needs.

INTRODUCTION

Participants in the Wildland Fire 2000 meeting in 1987 were assigned to futuring groups to outline a perception of trends, visions, and strategies for specific subject areas. (Davis and Martin 1987, Alexander and Andrews 1989). Among the key visions was the following:

> An internationally accepted family of fire occurrence and behavior systems would be available to serve the needs of fire management at all levels within the organization, from planning to operations for both wildfire and prescribed fire.

Another documentation of the recognition of the need for a common approach to fire behavior, fire danger, and fire management systems came from the Conference on Bushfire Modelling and Fire Danger Rating Systems held in Australia in 1988 (Cheney and Gill 1991). Following is a resolution proposed by B. J. Stocks, Forestry Canada:

> **International Memorandum of Understanding (MOU).**
> That the time is opportune for the development of a Memorandum of Understanding between Australia, Canada and the United States on fire danger rating and fire behaviour modelling. Decreasing fire research

resources in each country, coupled with the fact that the combining of empirical and physical modelling approaches is now seen as necessary, are strong reasons why an MOU that would facilitate cooperation and scientific exchange on a formal and consistent basis is necessary.

Discussions on this idea took place in conjunction with Fire and Forest Meteorology Conferences in Ottawa, Canada, in 1989 and Missoula, Montana, U.S.A., in 1991. A method of formalizing this cooperation has been determined, and the document is expected to be signed by the three countries by the end of 1991.

One of the stated reasons for cooperation is that a number of nations that lack independent fire research capability have adopted fire danger rating and fire behavior prediction systems developed in Australia, Canada, or the United States. A common approach would facilitate consistent application of fire management support systems by such nations. Successful application of systems depends upon initial selection of an appropriate system, provision of suitable data, and correct interpretation of outputs in the context of local conditions.

STATE OF CHANGE

The United States, Canada, and Australia all have a long history of developing fire danger and fire behavior prediction models and systems. All are in a state of transition, examining possible paths for the future. Now is an ideal time for us to define a common approach.

Among the reasons for the state of transition are opportunities offered by the availability of new technology: geographic information systems, satellite information, powerful personal computers and workstations, color graphics, improved communication networks, and so on. In addition, there is recognition of weaknesses in some currently used models and of research in progress that may correct some of those problems.

United States

The United States has many fire management systems that are based on Rothermel's fire spread model (Rothermel 1972, Andrews 1991). Those systems were developed by separate groups as needs arose. Three widely used national systems are the BEHAVE fire behavior prediction system (Andrews 1986, Andrews and Chase 1989, Burgan and Rothermel 1984), the National Fire Danger Rating System (NFDRS) (Deeming et al. 1977), and the National Fire Management Analysis System (NFMAS).

Rothermel's model (1972) is used as the core of those systems because it is well suited for examining potential fire behavior under various fuel, topography, and weather conditions. However, because it describes only the behavior of the flaming front of a surface fire, changes were made to some of the equations in NFDRS and NFMAS to include the effect of large fuels and to reflect seasonal trends. We recognize that an improved fire model is needed to overcome problems that have become apparent over the past 20 years. In addition, problems exist with "seams" between fire management

systems--inconsistencies and gaps. There is sometimes confusion in knowing which system to use for a given application.

The U.S. Forest Service's Fire Behavior Research Work Unit (RWU) is charged with development of an integrated fire management system (Rothermel and Andrews 1987). A structure will be provided for a system to support the full range of fire management activities. This includes real-time fire behavior prediction of wildfire behavior, prescribed natural fire planning, long-range severity forecasting, economic planning, etc. The Fire Behavior RWU will be involved in developing some of the models that will be used in the system and in designing and developing software for specific applications in the fire behavior/fire danger arena.

We are in the early stages of developing the system structure. We plan to do this in cooperation with other researchers and fire managers in the United States and, we hope, Canada and Australia.

Canada

The Forestry Canada Fire Danger Group has just reached the milestone with the release of the Fire Behavior Prediction (FBP) System, part of the Canadian Forest Fire Danger Rating System (CFFDRS) (Forestry Canada Fire Danger Group, in process). The Fire Weather Index (FWI) part of CFFDRS has been in application in its present form since 1976 (Van Wagner 1987). The Fire Danger Group is in the process of setting priorities for future work.

Fire behavior models for spread rate and fuel consumption were derived from data collected from experimental burning projects and wildfire documentation. The concept of "fuel type" in the FBP System remains purely descriptive and discrete, with separate empirical equations for each (Van Wagner 1990). Current models provide spread rate for a fire, fuel consumption, fire intensity, and degree of crown fuel involvement. Research in progress is aimed at determining conditions for the transition from surface to crown fire.

The Fire Danger Group has focused on development of models and on structuring them for use by fire managers. To this point, they have not been involved in developing software for operational use. This has been done by the private sector, user agencies, and other Forestry Canada projects (Lee and Anderson 1991, Kourtz 1987).

Australia

Among the several fire danger rating systems in Australia are the McArthur fire danger rating systems for forests and grasslands (McArthur 1960, 1967) and the Western Australia forest fire danger rating system for jarrah, karri, and pine forests (Sneeuwjagt and Peet 1979). These systems are based on the rate of spread of surface fire spreading in a standard fuel type. The basic relationships among rate of spread, surface moisture content, and windspeed were derived by eye-fitting curves to cover a range of expected weather conditions. Because the existing fire danger rating systems have been developed for specific fuel types, it is difficult to compare the fire weather or to appreciate the fire control problems in different regions (Cheney 1990).

Because there is not a national fire danger rating system in Australia, a resolution passed at the 1988 conference in Australia was as follows:

> **A National Fire Danger Rating System.**
> That the Fire Management Research Working Group promote the development of a National Fire Danger Rating System, with the aim of standardising Fire Danger Rating between States, and to ensure that both the public and fire managers develop a common understanding of fire danger.

As is the case in the United States and Canada, fire management systems are being designed in Australia to take advantage of available technology (Gellie 1990, Green et al. 1990).

FINDING THE COMMON APPROACH

As noted in the introduction, a first important step in finding common ground for future development of fire behavior, fire danger, and fire management systems has been taken--there is a recognition of need. Another important step is development of a fire model that would work for the range of fire behavior, fuel, and weather conditions around the world. Toward this end, researchers from the United States and Australia are cooperating on development of the next generation model for fire spread and intensity. A preliminary model being developed is based on physical principles and wind tunnel data. Completion of the model will involve other researchers from Australia, Canada, and the United States, and will use fire data collected in the field around the world.

Because various research groups already have similar visions of the next generation fire management systems and are taking similar approaches to modelling and system development, we expect to be able to find common ground. While some parallel work is healthy in that new ideas and new approaches are examined, in general we don't have the luxury of providing the resources (people and money) for excess duplication of effort. There are relatively few fire researchers in the world, there remains much about fire that we don't know, and there are fire management needs that haven't been satisfied. There's plenty of work to go around.

SYSTEM STRUCTURE

The word "system" can take on many meanings. As I use it here, **Integrated Fire Management System** does <u>not</u> mean one huge all-encompassing computer program that satisfies all fire management needs. Rather, it is a combination of manual and computer processes that satisfy the range of fire management needs, each of those processes being based on common building blocks.

Structured system design methods can be used to design the integrated system. We should begin by defining fire management needs: identifying the tasks done by fire managers and the decisions made in accomplishing those tasks. We can then examine the information that is needed to make those decisions and specify where that information will come from. Basic building blocks of the integrated system can be identified; for example, a fire spread model, a fire occurrence

data base, and a model for the probability of a surface fire becoming a crown fire. These building blocks can be used in various ways depending on the fire management task at hand.

Tables, nomograms, or slide rules might be needed for quick and easy field use. At the other extreme a GIS-based program might be developed to simulate the effect of various suppression options. In turn that simulation might be part of a system for long-term economic planning or a system for real-time dispatch of initial attack forces (both of which are part of the integrated fire management system).

Basing various applications on the same building blocks means that the wheel will not be continually reinvented--that software will not be continually rewritten. Training, implementation, maintenance, and support of fire management systems will be easier. When improved models become available, they can be easily tested and then added or substituted. Even if there are some basic differences in model preference or fire management philosophy, the system designer can easily substitute one building block for another.

It is unreasonable to think that there can be worldwide agreement on computer programs for fire management. Agreement among States, Provinces, or agencies may not even be possible. But I do believe that we can define a common approach in terms of basic building blocks and an overall system design.

IMPLEMENTATION

It will take quite some time to complete the planning, research, and development of an integrated fire management system. Involvement of fire managers in testing, training, and implementation is an important part of the process. The fire management community will go along with a change to the next generation fire danger, fire behavior, fire management systems if those systems meet their needs better than systems that are currently in place. I'm convinced that this will be so and that we will be able to report on it at the followup to the Wildland Fire 2000 conference, scheduled for the spring of 2001.

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Application of Fire Growth Simulation Models in Fire Management

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Abstract

A variety of fire management activities can include the use of a fire growth simulation model for decision support. The design of the simulation must depend on the application. Potential applications are discussed including short-term projections on a going fire, assigning priorities to multiple fires, long-term projection for a going fire, long-term projection for a simulated fire, long-term successional modeling, escaped fire situation analysis, long-term economic planning, and modeling potential fires within the urban wildland interface.

Résumé

Diverses activités de gestion des feux de forêt qui pourraient inclure la modélisation du taux d'accroissement des incendies peuvent servir à supporter les décisions. La conception d'un système de simulation depend de l'application. Les applications potentielles sont examinées incluant les projections à court terme d'un feu en marche, l'assignation des priorités lors de fuex multiples, des projections à long terme d'un feu en marche, des projections à long terme d'un feu simulé, la modélisation de la succession à long terme, l'évaluation des possibilités de suppression, la planification économique à long terme et la modélisation d'incendies potentiels dans la zone ou la forêt et la ville se rejoignent.

Introduction

Fire management decisions are often based in part on the use of mathematical models that offer a consistent and repeatable method of providing quantitative fire behavior parameters. The core of most fire management systems in the United States is a deterministic mathematical model for steady-state fire burning through uniform surface fuel (Rothermel 1972). When a fire growth simulation model is available, I am certain that it will be used as a decision support tool in many fire management decisions. In this paper I discuss potential applications.

Fire Growth Simulation Model

A fire growth simulation model could be used to calculate the spread and intensity of a fire burning through variable fuel and terrain, under weather conditions that vary over both space and time. The need for a fire growth simulation model is not a new idea (Van Gelder 1976, Kourtz et al. 1977, Frandsen and Andrews 1979). There is currently a lot of interest in this area of work, so much that I will not attempt to review it in this paper. A major reason for the recent activity is that computer hardware and software is now able to support this application. In particular, Geographic Information Systems (GIS) offer a means of storing, manipulating, and displaying spatial data.

Fire growth simulation models will likely hold a prominent place in the next generation fire behavior/fire danger rating systems in the United States. It will take a major effort to develop and fully integrate fire growth simulation models into the fire management decision process. This paper attempts to contribute to that effort by identifying decisions that will be aided by fire growth modelling. One of the three major tasks involved in developing systems of the future is the determination of user needs (Rothermel and Andrews 1987). We hope this paper will stimulate people to think in specific terms about how a fire growth simulation model can support fire management decisionmaking in the future.

A fire growth simulation model only approximates actual fire growth regardless of how much effort is put into developing it. Law and Kelton's (1982) state-

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

ments about simulation models in general certainly apply to the simulation of fire growth: "A simulation model should always be developed for a particular purpose. Indeed, a model valid for one purpose may not be valid for another. ... A simulation model should be validated relative to a specified set of criteria, namely, the criteria that will actually be used for decision making."

Short-Term Projection On a Going Fire

Projections of fire spread and intensity around the perimeter of a fire are used in selecting potential control points and in assigning suppression forces to a wildfire. Short-term prediction of the behavior of a wildfire is both an art and a science. Fire experience is essential to the prediction process. Fire Behavior Analysts (FBA's) currently use their experience and the steady-state fire model in making predictions according to methods described by Rothermel (1983). Vectors of fire spread are plotted from several key points around the perimeter. The overall fire growth is then sketched on a topographic map based on the FBA's judgment. Personal judgment is also used in defining the input for the calculations. For example, windspeed and direction are determined from measurements, forecasts, and topography.

A fire growth simulation model must be streamlined and easy to use to be useful as a tool to a FBA. Producing projections in a timely manner is critical. The simulation should produce maps that show current fireline location and probable fire growth given the best weather forecast. It may be used to develop a range of likely fire positions based on varied forecast information.

The model should be easy to use but not so fixed that personal expertise and judgment are not authorized. Although the simulation must include a method of determining variable windspeed and direction over complex terrain, there should also be an option to enter wind vectors directly. The FBA and meteorologist on a fire team may want to assign windspeeds rather than use the results of a wind model. Another example of the need for flexibility is related to the fuel information stored in the data base. Fuel mapping from interpreted satellite imagery is not 100% accurate. Although this procedure is adequate for many applications, it may not be acceptable for real-time fire behavior prediction if the small percentage that is misclassified falls in front of the fire. We must also allow for the possibility of correctly classified fuel having changed since the data base was last updated.

Assigning Priorities to Multiple Fires

In multiple large fire situations a fire growth simulation model could be used to compare the spread potential among fires competing for suppression resources. This could provide a basis for setting priorities relative to the kind of forces that should be assigned to each fire. In conjunction with economic models, this would help decision-makers judge the alternatives that are available to them.

Long-Term Projection For a Going Fire

There is a real need for a well-defined method of making long-term projections of the growth of a specific fire. This relatively new need results from fire management policies that in many cases allow options other than full suppression. A fire can be declared either a prescribed fire or a wildfire. And there are several levels of appropriate suppression action that can be taken on a wildfire. An important decision is made when a new fire start is declared a prescribed fire or a wildfire. A primary element to be considered is potential fire behavior. It is expensive and difficult to later reverse a decision that designated a fire as a prescribed fire.

An interagency fire management fire policy review team was established to review policies of the U.S. Departments of Agriculture and the Interior on fire management because of the fires in the Greater Yellowstone Area during the summer of 1988 (USDA/USDI 1988). Among other things, the team recommended that "Current fire management plans must be strengthened by ... Including a comprehensive set of criteria which will be used in deciding whether or not to allow natural ignitions to burn as prescribed fires." And "Line officers certify daily that adequate resources are available to ensure that prescribed fires will remain within prescription, given reasonably foreseeable weather conditions and fire behavior."

Regardless of how good a fire growth simulation model is, it is not possible to make fire behavior predictions without reliable weather forecasts. Nevertheless, fire managers must base a decision on what a fire might do weeks or months into the future, well beyond a 3-day forecast. Gaming can be used with a simulation model to examine possible outcomes based on historical weather records. Such questions as: What if the weather is the same as last year?, What if it is the most extreme weather on record?, What if a dry cold front moves through each of the next 5 weeks?, can be asked and answered instantaneously. Given this information fire managers will have to determine whether their decisions should be based on most probable or on worst case conditions and assess the element of risk that they are willing to accept.

Although this approach has been applied to some extent to currently available methods (Rothermel et al. 1988, Lukens and Krebs 1987), it is tedious and time consuming to look at more than a few possibilities. A fire growth simulation model could produce a multitude of projections based on various potential weather patterns in a relatively short time frame. The results could be presented as probabilities. In most cases it is not important to know exactly where the fire will be on a given date, but rather whether it will reach a certain critical boundary before it goes out or whether it will get larger than a given critical size.

In addition to being used as support for the decisionmaker, the results of fire growth simulations can be used as a means of communication. The resulting maps can be a focus for discussion among agency people. They can be used as a means for communicating the bases for decisions and recommendations to line officers and also for communicating the status of the fire and its potential to the public and the press.

Long-Term Projections of Simulated Fires

Simulations such as those described above for ongoing fires can also be done for hypothetical fire starts and used in the planning process. Simulation of fires in various locations in the management area under a range of weather conditions would help define an acceptable level of risk for designating a fire as a prescribed fire.

Development of the Absaroka-Beartooth Wilderness fire management plan used available technology to estimate the potential size and intensity of historical fires under the assumption that suppression action had not been taken (Keown 1985). Historical fires were matched with weather records, and potential fire behavior was calculated. The results suggested that fires would be relatively small, with low potential for large stand replacement fires. A simulation would allow this approach to be expanded to project fire behavior under weather conditions other than those under which historical fires occurred and to simulate additional hypothetical fire starts.

Long-Term Successional Modeling

Simulation models have been developed to assess the long-term ecological impacts of a fire management policy (van Wagtendonk 1985, Keane et al. in press). Such a simulation is run for a long period (e.g., 200 years) under various fire regimes (e.g., full suppression, lightning fire, 10-year fire interval). The simulation includes models for stand development and fuel accumulation. The use of GIS and a fire growth model will allow the addition of spatial relationships.

Escaped Fire Situation Analysis

The Forest Service objective for wildfire suppression on National Forest System lands is to suppress wildfires at the minimum cost consistent with land and resource management objectives. An escaped fire situation analysis (EFSA) is conducted when a wildfire escapes initial suppression action. It is used to determine the most appropriate suppression strategy for the particular situation. Reasonable suppression alternatives are identified, analyzed, and evaluated. Evaluation criteria include estimated suppression costs, resource loss, and environmental, social, and political considerations. The probability of success of a given suppression strategy is dependent upon factors such as fuel, weather, topography, fire behavior, and the availability and effectiveness of suppression forces. Probability of success is most often based upon judgment of members of the fire overhead team (Chambers 1985).

A fire growth simulation model would bring consistency into the development of the EFSA. The estimation of how big a fire is going to get or where it is going to burn under various suppression alternatives would be more objective. In addition, evaluation of long-term ecological effects could be better included in the decision process.

Long-Term Economic Planning

The National Fire Management Analysis System (NFMAS) is used by the Forest Service for identifying the most efficient fire protection budget level. The Bureau of Land Management and most of the States also use this system (Brandel 1987).

The NFMAS model considers only initial attack forces on nominally uniformly spreading fires. The process depends upon the development of a probability distribution of estimated sizes for large fires (the probable result given a failure in initial attack). "Presently this distribution must be based on historical fires since there is no objective way to generate a 'future history' based on current and expected fuel, weather, and other conditions that affect fire spread and size in a given area. Since this historic distribution reflects past conditions and large fire suppression actions, not current or future ones, a potential bias is introduced into the analysis." (Chase 1989)

The problem of how to interpret historical fire size data for the NFMAS model application is becoming even more complex with the possibility of escaped prescribed natural fires being included in the data base. A fire growth simulation model would eliminate the need to rely solely on historical fire data to generate the fire size distributions. In addition, a fire growth simulation model would allow the planning process to be expanded to include suppression options at points other than at initial attack.

Urban Wildland Interface

A fire growth simulation model can also be useful in planning at a site-specific level, such as is needed to deal with the urban wildland interface. Model results can be used in setting standards for safe development, planning protection requirements, and communicating with those who are not used to dealing with fire: land owners, developers, land use planners, government administrators, and elected officials.

A fire growth simulation model could be used to evaluate the probability of a fire spreading into a developed area. The behavior of a fire could be simulated under several weather scenarios, cool-wet-and-calm to hot-dry-and-windy. Graphic display of fire spread could project a fire safety message more effectively than words. A simulated fire could dramatically illustrate the effect of fuel treatment around homes and

the effect of prescribed fire around a developed area. A fire growth simulation model could help determine specific protection requirements, such as engine placement, and help determine the effect of pre-positioning initial attack forces. It could be used in planning fuel breaks and other pre-attack measures.

One of the more important uses of a fire growth simulation model might be in communication with people who are not used to thinking about fire. Irwin (1987) pointed out the importance of good display in communication: "the diagrams present a 'flat earth' character ... The average citizen, developer, planning commissioner, or elected official cannot grasp any realistic concept of the fire environment from these diagrams. Without that ability, final planning decisions tend to be less than adequate, if not detrimental to fire protection interests."

Summary

It will not be possible to develop a generic fire growth simulation model to satisfy all applications. A successful simulation system must be designed to meet specific needs. Consideration must be given to the source and resolution of the data required to run the simulation, the form of the results, and the interaction with the user.

Although all applications will require weather input, the source and resolution of that information will vary greatly. For example, shift projections on a wildfire require a spot weather forecast that is based on observations taken on site while a long-term planning application will use climatology and "what-if" scenarios.

The form of the output should be suited to the application. In some cases the actual fire location is critical; the user may want to watch a simulation of an hourly progression of fire growth. This level of resolution is unnecessary if the question is whether the fire will cross a critical boundry by the end of the fire season.

A fire growth projection may be for worst-case conditions, or most probable, or a range of values, or a probability distribution. In any case, display will be an integral part of the simulation. Color graphics can communicate information quickly and efficiently whether the result is a single fireline location or probability output.

Some applications need flexibility while others require consistency. A real-time fire growth model designed for use by an expert should be flexible to allow for expert opinion to override the model. On the other hand, an economic planning model should be designed for consistency and repeatability.

An overview of some of the potential applications of a fire growth simulation model is just a first step. It will take additional planning to design the systems for specific applications in the context of the fire behavior/fire danger rating system of the future.

It must be emphasized that in all applications, a fire growth simulation model will be designed to support decisionmaking. A person, not the model, will make the decision.

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Prepared for Northern Calif
Fuels Newsletter, Sept 1991

Use of GIS by Fire Behavior Research

GIS is an important tool in the work being conducted by the Fire Behavior Research Unit at the Intermountain Fire Sciences Lab in Missoula. We have three workstations and may need another by next year. We're doing our best to work under Forest Service project 615 standards. At present we're using the GIS public domain software GRASS, developed by the Army Corps of Engineers. GRASS is the GIS used by the National Park Service. Following is a summary of some of our GIS applications.

Yellowstone 88 fire growth data. We are developing a data base of the daily fire growth of the 1988 fires in the Greater Yellowstone Area (GYA). We digitized maps that were drawn during the fires, largely based on IR flights. Additional information was obtained from chronologies and from the files for each fire. We also used after-the-fact fire severity data as interpreted from satellite data.

Yellowstone 88 weather. Hourly weather for points on a grid over the GYA has been constructed using a model and available observed weather data. We are just beginning to examine this data using our GIS. We can, for example, calculate and display the Haines Index as it varies in time and space over the Park. We plan to look at the relationship between the Haines Index, an indicator of severe fire behavior, and the fire growth data. In addition, we are gaining a better understanding of the capabilities of a wind and weather model in complex terrain.

Yellowstone pre-fire fuel. We have a GIS data base of pre-fire vegetation for Yellowstone National Park. We're working on getting this data for the entire Greater Yellowstone area. Vegetation will be interpreted in terms of fuel, both for the surface fire model and the crown fire model. This fuel data along with terrain, weather, and fire growth data will be used to test the fire growth simulation model described below.

Seasonal change in live foliage. We are looking at NDVI (Normalized Difference Vegetation Index) obtained from AVHRR satellite data. NDVI reflects changes in biomass and moisture content of live foliage. We are exploring its application to fire management needs. NDVI is available weekly for the whole U.S. (soon to include Alaska). GIS is used for such things as displaying the data, comparing NDVI values from different periods, and summarizing NDVI values for a specified area.

National vegetation/fuel map. Another product based on AVHRR satellite data is a land classification map for the U.S. We plan to interpret the classification first in terms of vegetation and then as fuel. Fuel type will be more than the current fuel models since a fuel description is needed by the crown fire model as well as the surface fire model (a new one is under development), and by consumption models for smoke and fire effects. GIS will be an important tool in dealing with data at a 1 km resolution for the whole U.S.

Fire growth simulation. We're working on a fire growth simulation that can model fire behavior through nonuniform fuel and terrain with weather changing over time. It will include both surface fire and crown fire spread and will be designed to include both fire effects and smoke models. The simulation will be used for a wide range of fire mangement activities, from real-time prediction of an ongoing fire to 300 year models examining the effect of suppression policy on vegetation. The type of information (e.g. weather) needed to drive various applications is quite different. We have stepped back and reexamined our approach to development of the simulation. We're currently concentrating on an architecture (a Simulation Manager running under X Windows) that allows GIS-based models to be independently developed by other groups as separate stand alone programs and easily used with the simulation. We will make this as independent of the GIS software as possible. We recognize that there is value in cooperation among researchers and modelers on such an important tool for fire managers.

Wind/Weather models. We're examining available wind and weather models for use in complex terrain for incorporation into the fire growth simulation model and other parts of our future systems.

Integrated fire management system. We're working on the next generation of fire behavior/fire danger rating systems. Important parts of the system will be GIS-based.